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THE BOTANICAL REVIEW

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NITROGEN SOURCES OF SEED PLANTS AND ENVIRONMENTAL INFLUENCES AFFECTING THE NITROGEN SUPPLY[1]

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INTRODUCTION

This survey attempts to select from the voluminous literature on the nitrogen cycle, references relevant to little emphasized nitrogen sources and the nitrogen requirements of a number of seed plants. The review emphasizes general aspects of nitrogen conversion of interest to the plant scientist whose specialty is not microbiology, including interactions among the organisms concerned and environmental agencies which accelerate or inhibit nitrogen fixation or nitrification to the point of affecting agricultural practice.

Around 70 spermatophyte species are known to occur naturally in a particular gypsum sand deposit having a maximum concentration of only eight p.p.m. total nitrites and nitrates in the vicinity of a relatively luxuriant root growth (88, 251). Forty-four other species of vascular plants, seventeen of which are Compositae, are reported to grow on practically nitrogen-free soils (243). The explanation in all cases appears to be that plants of a low initial nitrogen requirement may grow in substrates which leach readily. Many soils, once crops start to develop, are practically devoid of nitrate because of its rapid uptake, though the amounts being liberated by soil organisms may be ample for good yields (37). Even in a prairie soil containing two or three tons of nitrogen per acre in the plow layer only a few pounds are available to plants at any one time (211). Nitrogen unavailability may sometimes result primarily from the absence of carbon to support a vigorous bacterial population (211). Recorded bacterial activity in certain South African soils can not keep pace with nitrogen losses from leaching and cropping (140).

The original source of soil nitrogen is nitrogen fixation, which is the reduction of atmospheric nitrogen to ammonia or derivatives of ammonia. Most species of *Azotobacter,* one of the two most important genera of nitrogen-fixing soil saprophytes, fix nitrogen only when this element is not otherwise available in sufficient quantities for growth of the microorganism (43). On the other hand, nitrogen fixation occurs symbiotically on a large scale in root nodules of *Alnus incana,* a non-legume (226), and has been reported for a number of other non-leguminous seed plants (178, 191, 149, 203, 243, 245, 246). Microorganisms capable of fixing soil nitrogen asymbiotically include certain saprophyte bacteria, in addition to the classical *Azotobacter* and *Clostridium* spp. (257, 263,

113, 177, 72); yeasts (107, 106, 244); other fungi (81, 33), some of which are mycorrhizal (189); and a number of blue-green algae (32, 102, 128). Some nitrogen is fixed by lightning.

Nitrification is the conversion to nitrates of soil ammonium compounds, formed originally in nitrogen fixation but in large part returned to the soil directly through plant and animal residues. Certain normal agricultural soils of North Carolina, inoculated at various times of the year into an ammoniacal solution, failed to nitrify, not producing enough nitrite or nitrate to react in the diphenylamine test (266). Such soils are probably exceptional, however. That non-biological phenomena may contribute to soil nitrification is evidenced by small increments of nitrogen in tropical soils upon exposure to light (74), the physicochemical oxidation of nitrite compounds at the surface of acidoid soil particles (230), and the spontaneous oxidation of nitrites to nitrates elsewhere in nature. Also, rain and snow return varying amounts of nitrogen to the soil (179).

The importance of the role of non-biological nitrogen fixation or nitrification in soil economy is accepted with some reservations, however (48). Observed evidences of nitrogen increases are sometimes attributable to errors inherent in the Kjeldahl method of analysis, which is inadequate where the criterion of fixation or nitrification is the difference in nitrogen content of substrates high in combined forms of this element (319).

I. ORIGIN OF PLANT NITROGEN

1. NITROGEN FIXATION. Biological nitrogen fixation is the reduction of atmospheric nitrogen to ammonia or derivatives of ammonia, such as amino acids, through the agency of living organisms (30). Nitrogen fixation, the initial step in converting atmospheric nitrogen to a form available to living things, is almost exclusively biological, the only further definitely known mechanisms being fixation by atmospheric electricity and by man's chemical syntheses (30).

a. Nitrogen Fixation in Seed Plants. At one time only five of 211 families of flowering plants were believed to fix nitrogen symbiotically. More recently *Rubus fruticosus, Aesculus hippocastanum, Linaria cymbalaria, Achillea millefolium, Helianthus scaberrimus, H. tuberosus* and *Iris germanica* have been reported to bring about an increase in nitrogen content of the sand substrate in which the

plants grow, exceeding that accountable for by rain (245, 246). The experimental conditions, however, did not exclude physicochemical or even microbiological reactions which increase total nitrogen. Ruderal, wall and desert plants as well as trees in general can live in practically nitrogen-free soils (243). It is possible that mycorrhizae are one nitrogen source for certain of these species, particularly for the trees. Other non-legumes reported to assimilate atmospheric nitrogen directly or symbiotically when this element is available in no other form include *Diplotaxis tenuifolia, Leontodon taraxacum, Bryophyllum tubifolium, Sedum glaucum, Echeveria multicaulis, Crassula perfossa, Sempervivum tectorum, Trichodiadema stelligera* (243), *Triticum* (178), *Calluna vulgaris* (149) and *Zea mays* (203). A number of other species, including *Raphanus sativus, Acer negundo, Cucurbita pepo* and *Polygonum fagopyrum,* are believed to assimilate some amount of atmospheric nitrogen directly (191). The use of isotopic tracers is in order in the further study of nitrogen sources of these plants (319). *Zea mays* is known to use ammonia in preference to nitrate where both are supplied in nutrient solution (183). If any form of atmospheric nitrogen is used directly by green plants, however, the amount appears to be insignificant compared with that absorbed by the roots in a combined form.

The symbiotic genus *Rhizobium,* commonly associated with legumes, fixes appreciable quantities of atmospheric nitrogen in organic combination. Symbiosis between the nitrogen-fixing bacteria and seed plants other than legumes may be fairly widespread (246). Nitrogen-fixing bacteria have been isolated from seeds and plant parts other than roots, and plants with a high rate of nitrogen formation, as blackberries and many Compositae, are associated with bacteria which fix nitrogen readily (245). Nodules containing nitrogen-fixing bacteria occur on leaves of *Chomelia asiatica* (234) as well as roots of *Eleagnus* spp., *Ceanothus americanus* (262) and *Casuarina* (201). *Actinomyces alni* produces tubercles on *Alnus incana* roots, and uninoculated alders which do not receive supplementary nitrogen soon die (226). The presence of root nodules gives alders a place similar to that of locust trees in nitrogen conservation (181).

Azotobacter vinelandii has been reported to stimulate clover to form nitrogen in the absence of nodules, but clover fixes no nitrogen in the absence of bacteria, which apparently supply plant tissues

with enzymes requisite for fixation (165). Neither *Rhizobium* cultures (15) nor excised nodules in nutrient containing oxaloacetic acid fix nitrogen alone (9). Excised root nodules which appeared to fix nitrogen in the absence of bacteria were shown to have been contaminated with *Clostridium* spp. (279).

b. Biological Nitrogen Fixation in Soil. Non-symbiotic nitrogen fixation varies with soil conditions, ranging from a few to more than 50 pounds per acre annually (179). Certain species of *Azotobacter* and *Clostridium* are the soil saprophytes most important in fixing atmospheric nitrogen, though a number of other bacteria and saprophytic soil fungi fix varying amounts (166). Physical and mechanical conditions of a soil determine whether *Azotobacter* or *Clostridium* predominates (54). The large numbers of anaerobes in certain Iowa soils are believed to assume an important role in nitrogen fixation, particularly at an acid pH (303, 304, 311). The doubling of the rate of nitrogen fixation in other soil samples when placed under anaerobic conditions confirms the importance of anaerobes (282). Addition of calcium oxide or calcium carbonate has little effect upon the numbers of *Clostridium* or the amount of nitrogen fixed by this genus (312). Possibly because of the acid reaction and low phosphorus pentoxide in wheat soils of New South Wales, *Azotobacter* is so sparsely represented there that nitrogen fixation by this group can account for only one-fourth to one-third of the nitrogen requirement of the wheat crop (144). Anaerobic nitrogen-fixing bacteria of the butyric acid bacilli group seem to be of almost constant occurrence in a soil where *Azotobacter* was found in only 27 out of 85 samples (145). The absence of *Azotobacter* from a number of soils in which the nitrogen content is maintained at a high level would indicate that non-symbiotic fixation is accomplished by *Clostridium* spp. (310).

These two groups of nitrogen-fixing bacteria are not autotrophic, each requiring an organic source of energy. While they are not so poorly adapted as nitrifiers to ordinary media, it is commonly necessary to use special enrichment for their isolation (58). Mannitol is the carbon source ordinarily employed in media for *Azotobacter* culture (6). Sucrose, yeast and sodium thioglycollate are added to an inorganic nutrient in isolating *Clostridium* spp. (6).

Most of the experimental work on nitrogen fixation by *Azotobacter* has been done on species *A. chroococcum* and *A. vinelandii.* A survey of 283 Colorado soils showed *A. chroococcum* in 210,

A. vinelandii in only two, and no *Azotobacter* in 27 per cent (115). *Azotobacter* is more widely distributed in irrigated than in dry land soils (115), and most species apparently fix nitrogen only when this element is not otherwise available in sufficient quantities for growth (43). In the presence of nitrates, amino acids and peptone, *A. chroococcum* utilizes the combined nitrogen of the medium (335).

Nitrogen fixation activity has been reported for a number of other saprophytic bacteria. *Azotomonas,* an aerobic, Gram-negative, non-sporulating rod capable of fixing nitrogen, occurs in cotton bolls, rice hulls and tropical soils (263). Two or three strains of *Aerobacter aerogenes* fix atmospheric nitrogen (257), and all strains accelerate nitrogen fixation by *Azotobacter* spp. (153). *Rhodospirillum rubrum,* a purple non-sulfur photosynthetic bacterium, fixes molecular nitrogen (113) with photoreduction of carbon dioxide (177). Species of the green sulfur photosynthetic bacterium, *Chlorobacterium,* and the purple sulfur photosynthetic bacillus, *Chromobacterium,* have given positive results in preliminary nitrogen-fixing experiments (177). The tropical aerobic genus, *Beijerinckia,* fixes atmospheric nitrogen (72).

Evidence of nitrogen-fixing bacterial symbionts has been demonstrated directly or indirectly in the insect species *Pterocallis juglandis* and *Aprophora salicis* (277), in insect groups Aphidida, Homoptera, Heteroptera, Orthoptera and Coleoptera (278), in the larvae of *Ips amitinus, I. chalcographus* and *I. typhographus* from Czech spruce forests (218), and in the woolly louse, *Schizoneura lanigera* (219). Experimentation suggests, however, that while *Azotobacter* may be associated symbiotically with aphids, there is normally no nitrogen uptake from the air by either organism (260). Nitrogen fixation by insect symbionts could only indirectly contribute to plant nitrogen sources.

The few nitrogen-fixing fungi include *Phoma radicis, P. r. callunae* and *P. betae* (33). Small amounts of nitrogen are apparently fixed by the yeast, *Mycoderma bispora,* isolated from a wood-boring insect (244), and by species of *Saccharomyces, Willia, Pichia* and *Torula* as well as by mycelium-forming *Endomyces vernalis* and *Penicillium glaucum* (107, 106). While reports that certain of the mycorrhizal fungi can fix atmospheric nitrogen do not stand up under experimentation (33), potatoes with endotrophic

mycorrhizae growing in a soil having only organic nitrogen are healthier than the controls lacking such mycorrhizae (189). Mycorrhizal hyphae are in a favored position as competitors for available nitrogen, however, where they are supplied by the symbiont higher plant with a readily utilized source of energy (239). Wheat seedlings infected with *Puccinia triticina* show a greater amount of nitrogen per gram than uninfected controls (81). There is a definite and certain correlation between the growth increments of Scotch pine, birch, aspen, alder and spruce trees and the total soil nitrogen content, indicating that the trees of the forests in question can make use of this element in whatever form it occurs, presumably with the aid of mycorrhizae or other symbiotic organisms (138).

c. Photochemical Nitrogen Fixation. Though the number of aerobic nitrogen-fixing bacteria in soils kept in the dark is approximately ten times as great as in similar soils exposed to light, the nitrogen increase is greater in iluminated tropical soils than those kept in the dark, suggesting that in warmer climates there is a photochemical fixation of nitrogen (80). Sucrose in the soil is known to oxidize somewhat more readily in the light than in the dark, possibly contributing to the biological fixation of slightly greater percentages of nitrogen (270), since *Azotobacter* utilizes the decomposition products of carbohydrate in fixing nitrogen instead of carbohydrate itself (307). Negative results were obtained, however, in experiments attempting to demonstrate photochemical nitrogen fixation (151). Artificial ilumination with a lamp producing radiation from 2000 to 900 Å caused no fixation of soil nitrogen (302). Ultraviolet radiation of sugar at room temperature does not produce ammonia, and neither ammonia nor oxides of nitrogen are formed in the non-biological oxidation of sugar (246).

d. Nitrogen Fixation by Blue-Green Algae in Soil and Symbiotically. Pure cultures of *Nostoc* (32, 128) and *Anabaena* fix atmospheric nitrogen while growing photosynthetically in mineral salt solution (32). *Anabaena azollae* fixes nitrogen which it supplies in symbiosis to the host plant, *Azolla caroliniana* (32). The nitrogen-fixing system in *Nostoc muscorum* resembles that of *Azotobacter* and *Rhizobium* in that all are sensitive to low concentrations of carbon monoxide and are specifically inhibited by hydro-

gen gas (49). Nitrogen fixation sometimes occurs in sandy soil by symbiosis among *Azotobacter, Oscillatoria* and *Gloeocapsa* in the presence of calcium and at a pH around 6.75 (196). Increase in the organic nitrogen content of water in the Keiukov water reservoir parallels the increase in number of the blue-green algae, *Microcystis* and *Rhabdoderma* spp. (4). The alga *Chlorococcum humicolum,* isolated in pure form from the coral roots of *Cycas revoluta,* grows well in a nitrogen-free synthetic medium, indicating the ability to fix this element (102). Though *Cycas revoluta* normally occurs in soil low in nitrogen, the stems, leaves and seeds have a nitrogen content approaching that of legumes, and the ratio of nitrogen in the plants associated with the alga to that of non-infected controls is 271 : 100 (332). Blue-green algae may fix significant quantities of nitrogen in rocky desert soils (103). The practical significance of blue-green algae as direct participants in the fixation of nitrogen in agricultural soils, however, remains to be determined (267, 268). Bacterial instead of algal activity is chiefly responsible for nitrogen fixation in rice fields of Bengal (55).

2. SOIL NITRIFICATION. Nitrification is the conversion of soil ammonium compounds in two steps to nitrates. It is necessarily preceded by nitrogen fixation or by ammonification which is the liberation of ammonia from plant and animal residues by actinomyces, filamentous fungi and a variety of bacteria. Nitrification is not an original source of nitrogen available to plants, since the nitrogen in the compounds involved must at some previous time have been combined by fixation.

a. Microbiological Nitrification. Each of the two stages of nitrification may be effected in the soil by several bacterial genera. Ammonia tends not to accumulate, being converted into nitrites and nitrates as soon as it is produced (230). Nitrifiers ordinarily act at the surface of soil particles in the vicinity of the sites where ammonia is adsorbed (170).

The nitrifying bacteria are classified into two main categories (325), the nitrite-forming group, including five genera: *Nitrosomonas, Nitrosococcus, Nitrosocystis, Nitrospira, Nitrosogloea;* and the nitrate-forming genera, *Nitrobacter* and *Nitrocystis* (38). *Nitrosomonas* forms nitrites from ammonia and reduces nitrates to nitrites (231). Nitrifiers are autotrophic, not ordinarily growing on organic media (58). The inhibitory action of organic com-

pounds on nitrifying bacteria is on growth, not on nitrification (30). With both *Nitrosomonas* and *Nitrobacter* growth and formation of new cell substance are at the expense of carbon dioxide, and the energy required for reduction of the carbon dioxide is obtained from the oxidation of ammonia or of nitrite (30). Like most bacteria concerned with the nitrogen cycle, nitrifiers occur so sparsely in the soil that they can be obtained in plate culture only after repeated transfers through enrichment media. *Nitrosomonas* and *Nitrosococcus* can be isolated from soil samples added to media including small amounts of dipotassium phosphate, magnesium sulphate, sodium chloride, ferrous sulphate and ammonium sulphate (6). The media recommended for culture of *Nitrobacter* differs only in containing sodium carbonate and in that sodium nitrite is substituted for ammonium sulphate solution (6). Isolation of these three nitrifying organisms from the enrichment media is completed by streaking on plates of silica gel (6).

A group of nitrifying organisms distinct from the above is reported to occur in soil and in a sugar-beet effluent bed (66).

Heterotrophic bacteria include nitrifiers, many such organisms having been reported in the Great Lakes (194), sea water, sewage and soil (154). Sewage nitrifies freely in running streams (266). Of 81 strains of bacteria isolated from water, soil, sewage, compost and animal feces, 37 produced nitrite in aqueous suspensions of soil, sewage and compost materials (223).

Nitrification appears to be a much more common phenomenon in the sea than can be accounted for by the nitrifying bacteria which have been demonstrated (333). This discrepancy may be due to the inadequacy of the experimental methods employed (333). Beyond the zone of land drainage, surface sea water has few or no nitrifying bacteria, but active populations of nitrifying organisms are found in bottom deposits (300).

b. Photochemical. Ultraviolet radiation simultaneously oxidizes ammonium ions (233, 59) and reduces nitrate ions in solution to nitrite (63), two reactions also catalyzed by soil alone (64). In certain South African soils nitrification is attributed largely to photochemical oxidation at the soil surface (140), following adsorption of atmospheric ammonia on soil colloids (139). Oxidation of insignificant amounts of nitrites occurs in sterilized grassland soils of India mixed with ammonium salts and exposed to light in glass

vessels for 700 hours (74). While negligible or no evidence of photochemical nitrification was observed in sterilized controls or unsterilized soils exposed to light by a number of other workers (104, 73, 302, 256, 299, 152), small increments in soil nitrogen do appear to occur in this way under tropical conditions (181).

c. Physicochemical. Nitrites continually oxidize to nitrates in soil independently of microbiological or photochemical phenomena. This seems to be the reason why in nature nitrates occur in abundance and nitrites in only small quantities (230). Sodium nitrite and other nitrite salts are so highly unstable as to be infrequently available in a pure form (230). In a black cotton soil freed of exchangeable bases and agitated with water and 0.1 *N* KNO_2 in a mechanical shaker for various periods, the oxidation of KNO_2 to KNO_3, independently of light, began almost instantaneously, in 13 hours oxidizing 50 per cent of a total of 0.8496 gm. mixed with five gm. of soil and made up to 100 cc. with water. No bacterial agency could effect such huge conversions under normal conditions, and no bacteria could have survived the treatment with 0.05 *N* HCl to free the soil of exchangeable bases. Only 0.08 gm. of KNO_2 can be oxidized in an unshaken control in the same time interval, however (230). Base-saturated soils shaken with nitrite solution for one month show no oxidation of nitrites, a possible explanation of the decreased productivity of highly alkaline soils (230). Sandy soils are like liquid in that the distribution of ions is relatively uniform, while clay soils behave more like solid media, which explains the irregular distribution of nitrates and other ions at neighboring points in an apparently homogeneous section of tight soil and the activation of biological processes by tillage (69) or by the mechanical agitation applied in the above experimental study.

Small amounts of nitrates have been produced in the absence of nitrifying bacteria by bubbling carbon dioxide through a nitrate solution for about eight hours (233).

Nitrous oxides formed by lightning are carried to the soil in rain water. An average of 3.97 pounds per acre of nitric and ammoniacal nitrogen was brought down by rain annually at Rothamsted (242), while at Ithaca, New York, with approximately the same amount of precipitation, 12.5 pounds of nitrogen per acre were returned to the soil annually by rainfall (313). Nitrogen, present in rain and dew in amounts of one part per 10,000,000 to two

p.p.m., may be absorbed directly, in part through the leaves (200). Rain and snow also bring down much of the dust carried in air currents, a nitrogen increment which is much greater in industrial and thickly populated regions than elsewhere (179). It has been estimated that in certain parts of the world rain may in five or six years bring down sufficient nitrogen for the average wheat crop (144), though rain water also has a leaching action which varies from one soil to another.

When rain or irrigation leaches nitrites and nitrates from superficial soil layers in contact with air, rapid nitrification occurs, particularly intense at relatively high temperatures, which appears to be a purely physicochemical phenomenon independent of microorganic activity (241). Physical chemists consider that the vast deposits of nitrate occurring naturally in the earth as saltpeter and other compounds were formed in physicochemical instead of biological reactions.

II. EFFECTS OF OTHER ORGANISMS ON THE NITROGEN SUPPLY

1. SEED PLANTS. The presence of higher plants affects certain microorganisms more than others, causing only a slight increase in nitrogen-fixing bacteria and actinomyces and possibly influencing seasonal fluctuations in these organisms where the changes do not appear to be related to temperature and moisture (265). The effect of legumes on the soil microflora may be no more pronounced than that of non-legumes (265). Intact roots of lucerne or clover appear ordinarily not to excrete organic nutrients which affect *Azotobacter* (146). Rice and certain legume crops stimulate nonsymbiotic nitrogen fixation by *Azotobacter* and *Clostridium* (185, 250), while wheat roots and radish roots have a beneficial effect on *Azotobacter* (285). Alkaloids of *Lupinus angustifolius* in concentrations of 0.01–0.1 per cent accelerate growth of *Rhizobium leguminosarum* on synthetic media (182), though *R. leguminosarum* can not fix atmospheric nitrogen in the absence of a host plant (15). Peas may excrete from ten per cent to almost 80 per cent of the nitrogen fixed, the amount depending largely upon temperature and light conditions (30). Regular excretions of nitrogen occurring from roots of chick pea are beneficial to both the growth and nitrogen content of associated wheat plants (188), the relative effi-

ciency of the nitrogen fixation mechanism appearing to be greatest when the ratio of chick pea to wheat is one to two (188). The beneficial effect of the association of chick pea on the growth of wheat, however, is neither marked nor constant (188), apparently in part because the conditions for abundant nitrogen excretion are apparently those which favor abundant nitrogen fixation but discourage plant growth (30). Also, the amount of nitrogen used by crops is sometimes small compared with that removed from the soil by other means. Of the nitrogen lost from certain wheat soils, only 28.7 per cent was in the harvested crop, leaving 71.3 per cent unaccounted for (36). The decrease in soil nitrogen is sometimes largely attributable to zymogenous soil microflora which by its intense competition exhausts the supply of available nitrogen where an easily utilized energy-yielding material is present in excess (239). Observations on the soil bacterial flora have led to improved methods for composting or green manuring to avoid the harmful effects from crop residues in soil (58).

Nitrogen excretion by legumes may be of less importance under field conditions than the decomposition of sloughed off root tissues (30). The bacterial population liberated in the soil where nodular tissue decomposes is transitory, probably not surviving for as long as one year. There are no more root-nodule bacteria for soybeans in plats that have grown soybeans as recently as two to three years than in soils from plats that have not grown soybeans for 20 to 25 years (316).

Both growth of and nitrogen fixation by algae in rice soils are considerably increased by the presence of the crop as a result of the greater supply of carbon dioxide evolved in respiration and decomposition (68).

During the growing season more nitrate is formed in cultivated soil than in sod, and more on fallow than on cropped land (56). Yet in virgin soil of 21 Utah dry farms, nitrogen is 14.5 to 15.9 per cent higher in the surface foot and ten to 14.6 per cent higher in the second foot than in cropped land (36), apparently because of nitrogen depletion by the crop. A fallow area, not having the same competition as sod or cultivated soil for plant absorption, is higher in nitrates (41). In all seasons nitrate nitrogen, moisture percentage and average numbers of bacteria are highest in fallow land and least in sod (205). On fallow land the accumulation of

nitric nitrogen occurs in the latter part of the summer and early fall, though soil moisture conditions are more favorable earlier in the season (35). Most of the available nitrogen found at the end of the summer period in fallow land is located the following spring, but at a slightly lower depth (35). Unless cover crops are grown, most of the nitrates produced during the fall and winter in cultivated Arkansas soils are lost before spring (17). On a dry farm soil all of several experimental treatments resulted in nitrogen losses except where peas were rotated with winter wheat, and the greatest nitrogen loss occurred on plots cropped every third year with two clean intervening fallow periods. This was followed in order by permanent fallow, two crops in three years, and alternate wheat and fallow, with continuous wheat lowest in the cropping tests (120). Nitrate accumulation is low under a crop of celery, irrespective of whether the land has been in clean fallow or a cover crop has been turned under (204).

The prolonged use of inorganic fertilizers in crop rotation without grassland intervals decreases nitrifiers, and soil nitrification drops while cellusolytic fungi and myxobacteria increase (199). Application of a grass mulch decreases initially high nitrate in Uganda soils, and the onset of rains causes both the rise in nitrate on a bare soil and the decrease under mulch (122). Many factors influence the interconversion and accumulation of nitrogenous compounds, however, and in certain Alberta soils fluctuations in nitrate nitrogen do not correspond closely to fluctuations in numbers of bacteria, fungi or actinomycetes (205) believed to be active in the nitrogen cycle.

2. PROTOZOANS. Protozoans generally stimulate nitrogen fixation (129). The feeding action of *Amoeba* spp. (100), *Colpidium colpoda* or *Hartmanella hyalina* on *Azotobacter chroococcum* has a stimulatory effect on nitrogen fixation by this species, apparently by maintaining *Azotobacter* efficiency for a longer period (65). The presence of *Vorticella* increases bacterial nitrite production up to a maximum of 3.8 p.p.m. (223).

3. GREEN ALGAE. A hot water extract of the algae *Chroococcum*, *Pleurococcus* and *Chlorella*, as well as the medium in which the algae have been growing, favors growth and nitrogen fixation by *A. chroococcum* in mannite solution, and the green algae are

possible activators in the soil (308). Algal growth in rice fields, however, does not provide a suitable medium for the growth of *Azotobacter,* nor does *Azotobacter* utilize dead algae as a source of energy in nitrogen fixation (271). The indirect role of the majority of soil algae in the fixation of atmospheric nitrogen is limited or non-existent (267).

4. OTHER BACTERIA. Under proper conditions of moisture and oxygen, symbiosis exists between *Azotobacter* and cellulose-decomposing bacteria (190). A group of bacilli, including certain species of *Corynebacterium,* which are facultative anaerobes and ferment cellulose with the production of organic acids, provide *Azotobacter* with substances serviceable in nitrogen fixation (145). *Serratia marcescens, Bacillus subtilis* (26) and *Aerobacter aerogenes* convert part of the insoluble soil nitrogen into a soluble form (27). Small non-spore-forming rods which reduce nitrate to nitrite, and most of which ferment cellulose, have been isolated from soil around roots of cultivated plants where they may live symbiotically (164). Cellulose fermenters reduce nitrate as rapidly as it is formed when nitrogen is present in the soil in a ratio of less than one part nitrogen to 35 parts cellulose (12). An aerobic spore former isolated as a contaminant from a culture of *A. vinelandii* markedly stimulates nitrogen fixation by this organism if the medium does not supply an optimum amount of available iron (176). Nitrogen fixation by *Azotobacter* increases as a result of simultaneous inoculation with *Radiobacter* (209). Twenty-five cultures of actinomyces isolated from soil, however, inhibited *A. vinelandii* on nutrient agar (206). The presence of *Bacillus mycoides* along with *Rhizobium meliloti* causes better growth in sweet clover than in strains inoculated with *R. meliloti* alone (87), though 42 to 92 per cent of the sporulating bacteria used experimentally show antagonistic reactions toward *Rhizobium,* and their antibiotic agents responsible for this antagonism, when partially purified, yield comparable results (51). An organism of the *Bacillus mesentericus* type, isolated from low moor peat and leaf mold, inhibits growth of *Rhizobium* and *Azotobacter* (298).

Nitrogen fixation by lucerne and white clover in agar or sand cultures is not significantly stimulated by the presence of *A. chroococcum,* and high numbers of *A. chroococcum* prove harmful to the plants, possibly because of the excess production of heteroauxin

(146). Competition exists among different strains of nodule bacteria (291), an inefficient strain sometimes preventing the entry of an efficient one into host roots (273).

III. INFLUENCES OF pH ON NITROGEN FIXATION AND NITRIFICATION

1. NITROGEN FIXATION. Aerobic bacterial nitrogen fixation occurs only in well-aerated alkaline soils (163). For 40 strains of *Azotobacter* the maximum hydrogen ion concentration compatible with growth varies between 5.5 and 6.0 (108), the optimum pH range for *A. agile, A. vinelandii* and *A. chroococcum* is between 7.3 and 8.0 (28), and neither *A. chroococcum* nor *Rhizobium leguminosarum* survives at a pH below 4.5 (23). The optimum pH range for the growth and activity of *Bacillus amylobacter* is 6.0 to 7.0 (166).

Alkali soils increase in nitrogen-fixing ability upon leaching (117). Addition of ammonium salts to alkaline soils causes stronger nitrogen fixation than addition of organic matter, the reverse of the action of these two additives in acid soils (105, 163). Anaerobes are believed to assume an important role in nitrogen fixation at an acid pH (311). Nitrogen fixation by *Clostridium* occurs only in the presence of decomposable organic matter and is characteristic of all soils made acid by humus from plant residues (112).

Slight alkalinity favors nitrogen fixation by blue-green algae (103). The fixation of nitrogen by bread yeast is a function of pH, the two optimal concentrations being 6.0 and 7.9 (107).

Bacteria associated with alfalfa usually fix atmospheric nitrogen satisfactorily only when the pH is as high as 6.5 (281). Soil pH affects activity of nodules in alfalfa more than the formation of new nodules, which is increasingly depressed at pH 5.5 to 5.6 or less, but in clover the number of nodules more often increases at acid reactions (147). Soil acidity is beneficial to nitrogen fixation by soybeans, and soybeans change the soil reaction toward the acid side by two pH points when started in a medium of pH 7.05 to 7.18 (127). Soybeans planted in a soil of pH 5.6 to 6.37 fix more nitrogen, however, contain more total nitrogen, and absorb more calcium and less silica from the soil (127). The pH values of tops and roots of the same plant vary widely, but those of nodules of 12

legume species examined were within the narrow range of 5.5 to 6.4 (317). *Rhizobium* may shift the soil pH toward alkalinity with production of basic nitrogenous compounds or may increase acidity by formation and accumulation of organic acids from carbohydrates in plants (317).

The proportion of fungi appears to follow pH rather than climatic factors (261), but the ratio of fungi to bacteria plus actinomycetes in certain soils can not be correlated with pH. Aerobic nitrogen fixers present in forest soils at pH values as low as 4.6, but absent at a less acid pH and narrow calcium : magnesium ratio (142) are probably actinomycetes.

2. NITRIFICATION. The pH optimum for *Nitrosomonas, Nitrosocystis, Nitrospira* and *Nitrobacter* varies from 7.0 to 7.2 at the lower end of the range to 9.2 at the other extreme with little or no activity by any strains below 6.0 (325). Although nitrification is known to occur at a pH as low as 2.9, and acidity itself is probably never the inhibiting factor (238), nitrification is higher in soils having an alkaline reaction. The pH values of desert soils must be reduced to 7.7 plus or minus 0.1 before complete oxidation of ammonia to nitrate occurs and before nitrates accumulate in appreciable quantities (193). Addition of various amounts of sulfuric, citric or tartaric acid intensifies nitrification in chernozem soils and suppresses it in decomposed soils, increasing calcium and water-soluble phosphorus pentoxide in both soil types (167). Nitrification occurs in acid soils only if carbonates are present (5). Carbonate is essential for the nitrifying action of *Nitrobacter* in the oxidation of ammonium sulfate (326). Acid soils bearing *Pinus sylvestris* and *Betula pubescens* were found to contain no nitrifying bacteria (34).

IV. RELATIVE EFFECTS OF DIFFERENT MINERAL ELEMENTS ON ORGANISMS ACTIVE IN THE NITROGEN CYCLE

Phosphorus fertilization favorably influences *Azotobacter* development (19) and its rate of nitrogen fixation (236). Addition of superphosphate at the rate of 100 pounds/acre does not affect the longevity of *Azotobacter* introduced into a Geary silt loam having a pH value below 6.0 and from which *Azotobacter* is naturally absent, however, though the pH increases to 6.5 as a result of the treatment (110). The presence of *Azotobacter* in Iowa soils is

most closely correlated with pH, next with available phosphate, and still less with total nitrogen content (60).

Use of superphosphate increases symbiotic nitrogen fixation in *Trifolium alexandrinum* and results in greater wheat yields in rotation (216). For maximum nitrogen fixation alfalfa requires more phosphorus pentoxide than most soils contain (13). Addition of phosphorus pentoxide and potassium causes an increase in number, but not in size, of nodules (228) and in per cent nitrogen content of legumes grown in subsequent years in legume-grain crop rotations (237). Given proper amounts of phosphorus and potassium together, legumes grown in greenhouses may increase nitrogen fixation as much as 30 per cent (237). Nodule metabolism is influenced more by the concentration of phosphate than by the amount of potassium, however, and too much potassium inhibits nitrogen fixation (228), often acting as a respiratory poison as in the case of potassium oxalate (97).

Calcium stimulates aerobic nitrogen fixation more than potassium (126), which accelerates carbohydrate production (101), and the influence of calcium is more pronounced at low potassium levels (126). Non-symbiotic nitrogen fixation in many soils, however, is accomplished by *Clostridium* spp., which require no lime (310). In a medium kept below pH 6.0 calcium has no measurable effect on *Azotobacter chroococcum* which grows readily at, but not below, pH 6.1 to 6.5 (109). Increasing soil alkalinity by addition of calcium ordinarily increases nitrification (39), protein decomposition and numbers of bacteria (235). Under nitrification conditions soils high in active calcium ions accumulate much more nitrite as an intermediate stage in the oxidation of ammonia than do soils low in active calcium, which oxidize nitrite to nitrate at a faster rate, an effect not attributable to pH (123). Calcium sulfate prevents loss of nitrogen from manure, reacting with volatile ammonium carbonate to form non-volatile ammonium sulfate (20). When a soil is perfused with ammonium sulfate solution nitrification occurs at the surfaces of soil particles where ammonium ions are combined or adsorbed instead of in the soil solution (170). Upon addition of calcium ions to the perfusate, the rate of nitrification diminishes in proportion to the amount of ammonium ions displaced from the soil surfaces by base exchange with calcium (170). The nitrification rate is proportional to the fraction of total ammonium

ions adsorbed on the base-exchange complexes of the soil, independently of ammonium ions in solution (170).

As more calcium becomes available to nitrogen-fixing bacteria in soybean roots, nodulation and nitrogen fixation increase (3). A divided root system of an inoculated legume shows restricted beneficial effects in parts in contact with calcium carbonate for ten days before transplanting (2). Best nodulation occurs when both plants and bacteria receive calcium, but when neither is supplied with calcium no nodules form (186).

The elements most important as nutrient for legume bacteria, in order of decreasing activity, appear to be calcium, magnesium, barium, potassium and hydrogen (186). Nitrogen fixation by saprophytes increases in many western soils with the accumulation of plant residues, leaching of alkali and addition of the following elements, listed in order of decreasing action: sodium, calcium, iron, magnesium, manganese and potassium (117). In Arizona's cultivated non-acid soils, however, water-soluble calcium, sodium, magnesium, phosphate, chloride or sulfate content is not closely correlated with *Azotobacter* activity (192). Sodium nitrate increases growth of many microorganisms, but retards or even inhibits *Azotobacter* (19). Since *Azotobacter* spp. can utilize ammonium salts, nitrites and nitrates, inorganic soil nitrogen (95) or compounds readily converted to ammonium ions (322) decrease the nitrogen-fixing activity of this species. Nitrogen fixation by *Rhizobium leguminosarum,* however, occurs in a soil containing up to 1500 pounds of sodium nitrate or 1000 to 2000 pounds of nitrogen per acre as clover tops (1).

As much nitrogen fixation by cowpeas may be expected in a soil containing 3000 pounds of total nitrogen per acre as in soils with lesser amounts (1). Supplying combined nitrogen as ammonium nitrate, ammonium sulfate or sodium nitrate in quantities corresponding to the normal rate of nitrogen fixation in soybeans, however, practically inhibits nitrogen fixation, though considerable development of nodules still occurs (147). The depressing effect of nitrate ions on nitrogen-fixing activity appears to be associated with the direct use of nitrate by the plant (114).

The essential roles of magnesium and iron in nitrogen fixation are indicated by an approach to no growth in *Azotobacter* at the lowest concentrations (134). The toxic effects of copper and zinc

on soil nitrification are less in organic than in mineral soils (173), apparently from adsorption of the metals on colloidal surfaces. A soil copper deficiency is biologically detectible by increased nitrifying power following the addition of copper (173). Concentrations of from 600 to 2000 p.p.m. of arsenic in soils do not adversely affect the nitrification of cottonseed meal (331). In concentrations of 1 : 100,000, K_2SeO_3 increases the ammonification power of bacteria, while K_2SeO increases the nitrification ability, but both salts exert a toxic action at higher concentrations (184). Addition of lead, manganese, boron, fluorine, copper, zinc, arsenic or iodine in amounts of 2.5 and 10 mg./kg. of soil containing 4.5 per cent organic matter, 0.012 per cent nitrates and 1.8 per cent calcium at a pH of 6.9 catalyzes the production of greater amounts of nitrates than in untreated soil (175).

Moderate concentrations of heavy metals exert an inhibitory effect on the fixation of nitrogen by *Azotobacter agile,* presumably by reaction with the COOH group of the catalyst, while compounds which react with the basic group of the catalyst are stimulatory (93). Though neither growth nor nitrogen fixation in *A. chroococcum* is increased by concentrations of 1 to 100 p.p.m. boric acid (195), a dilution of 0.0005 M produces a 40 per cent increase in nitrogen fixation over the control (93). Certain other soil boron treatments have a similar stimulatory action (150), and a boron deficiency appears to cause symbiotic bacteria to live parasitically on cells of the nodule (84).

While molybdenum is essential in the nutrition of a number of organisms, including higher plants, the molybdenum requirement of *Azotobacter* grown on fixed nitrogen is lower than the requirement when grown with molecular nitrogen, suggesting that molybdenum may play a role in nitrogen fixation (30). Molybdenum and related elements in amounts as low as two p.p.m. are believed to catalyze nitrogen fixation by *Azotobacter* (181), possibly through molybdenum acting as a reducing agent (42). Addition of molybdenum increases nitrogen fixation by certain *Azotobacter* spp. ten- to 30-fold (135). The absence of *Azotobacter* from various localities on the Monterey Peninsula, California, is attributed to a molybdenum deficiency (288). Molybdenum may, to a certain extent, be replaced by vanadium (31). Traces of molybdenum also accelerate growth and nitrogen fixation by *Anabaena, Nostoc* (32)

and *Clostridium butyricum* (148). Legume seeds ordinarily contain larger amounts of molybdenum than seeds of other plants, and the root nodules of clover, vetch and lupine contain two to five times as much molybdenum as their seeds, supporting the hypothesis that molybdenum in root nodules has a role in nitrogen fixation (290). Legume responses to molybdenum treatment are most significant where nitrate or ammonium nitrogen supplies are inadequate (11).

Salt concentrations of 0.5 to 1.0 per cent stimulate *Azotobacter* growth (309), but species of this genus are completely inhibited by a salt concentration of 1.75 per cent (86). In Bedford silt loam at 66 per cent of water-holding capacity, potassium chloride in concentrations between 190 and 380 p.p.m. inhibits nitrite, but not nitrate, formation as a result of the action of the chloride rather than the potassium ion (125).

V. OTHER CATALYSTS OR ACCELERATORS INVOLVED IN NITROGEN FIXATION AND NITRIFICATION

Certain strains of legume bacteria form nodules on roots, but do not fix atmospheric nitrogen. These nodules differ from those of effective strains in lacking a red pigment having an iron content of 0.29 per cent and much like hemoglobin of the blood (180). This pigment is confined to nodules and is absent from the root system proper as well as from other types of nitrogen-fixing organisms such as *Azotobacter* (30). Opinion differs as to whether active root nodules of leguminous plants contain three interconvertible pigments, hemoglobin (red), methemoglobin (brown) and a green pigment with a porphyrin ring system closely related to the first two (294), or whether there is only a mixture of hemoglobin and oxyhemoglobin, no methemoglobin being detected in certain plants kept in the dark for several days (157). On bright days root nodules of vigorously growing legumes are red, indicating large amounts of hemoglobin and an associated high nitrogen-fixing capacity, while on cloudy days a low nitrogen-fixing activity is associated with a brown color (294). Variations of the total iron content of the nodules, however, do not regularly coincide with fluctuations in nitrogen fixation (297). Strains of *Rhizobium leguminosarum* which cause nodulation but do not fix nitrogen are covered by a slimy layer which prevents oxygen uptake and at the

same time inhibits formation of the red pigment (293). Within legume root nodules the red pigment displays the property of oxygenation characteristic of hemoglobin: $Hb + O_2 \rightleftharpoons HbO_2$ (157). The stimulatory effect of hemoglobin on the rate of oxygen uptake by bacteria directly from soybean nodules and by washed suspensions of *Rhizobium trifolii, Escherichia coli* and *Torula canadensis* at low oxygen tensions is somewhat more marked than the effect of the red pigment from leguminous root nodules (180). While a parallelism seems to exist between hemoglobin content of nodules and nitrogen-fixing ability (296, 297), extracts of this pigment from pea and soybean nodules will not induce fixation by free-living cultures of root nodule bacteria (210). Neither cells of legumes alone nor the symbiont, *Rhizobium,* can synthesize the hemoglobin independently (156), *Rhizobium* supplying the stimulus for proliferation of legume cells and also a factor necessary for hemoglobin synthesis.

While *Rhizobium* produces indoleacetic acid from tryptophane, and application of indoleacetic acid in high concentrations to pea roots produces nodule-like swellings, many other organisms which produce indoleacetic acid do not produce nodules (30). It is likely that a more specific agent than indoleacetic acid alone is involved in nodule production (30).

The content of hydrogenase, demonstrated in *Azotobacter vinelandii, A. agile* and *A. chroococcum* (314), is correlated with the functioning of the nitrogen fixation reaction (168), and sources of combined nitrogen which readily inhibit nitrogen fixation by *Azotobacter* also retard hydrogenase formation (169). The systems responsible for the oxidation of hydrogen and nitrogen fixation may possess common components (169). The fact that nodules of leguminous plants lack hydrogenase indicates that it may not be generally involved in biological nitrogen fixation (30), but in legumes fixation appears to be associated with the readily oxidized or reduced hemoglobin. Nitrogen is fixed by combination with hydrogen rather than with oxygen, which from the standpoint of energy makes it more efficient than the electrochemical process (307).

Cell division in *Azotobacter* is linked with increased respiration, while in nitrogen fixation the respiratory level is constant and cell division ceases (141). Cell proliferation and nitrogen fixation by *Azotobacter* are influenced to different degrees by mercury, mag-

nesium and iron (91). Similarly *Azotobacter* sugar utilization in respiration and nitrogen fixation shows differential reactions to boric, molybdic and phosphomolybdic acids (93) as well as to alcohols (97).

Elimination of radium and other radioactive elements from the nutrient prevents the formation of root nodules on peas; upon addition of traces of radium, root nodule bacteria develop and assimilate nearly twice as much nitrogen as in controls (83).

Decomposition of mushroom mycelium releases nitrogen from humus, lowers soil acidity and causes better growth and a dark green color in plants (202).

Excretion of amino acids from nodules occurs, sometimes in large quantity (292). Occasionally this excretion is as much as 80 per cent aspartic acid, the best nitrogen source for legumes, but unavailable to barley and wheat (292). Experimentally cystine and DL-methionine increase nitrogen fixation by *A. chroococcum* approximately 20 per cent (118). Tyrosine, DL-isoleucine, hydroxyproline and L-histidine greatly increase nitrogen fixation by this organism, while casein and albumen exert a lesser stimulus (118).

The extent and rate of nitrogen fixation by *Clostridium pasteurianum* are increased two- to three-fold through the use of shaken cultures and other technical improvements (240). Removal of metabolic carbon dioxide during fermentation appears to accelerate nitrogen fixation, but addition of molecular hydrogen to the atmosphere has no inhibitory effect (240). This response to hydrogen differs from that of aerobic agents of fixation—*Azotobacter, Nostoc* and symbionts—suggesting that the mechanism of fixation by *Cl. pasteurianum* is different, that the action of molecular hydrogen is dissimilar to that of metabolic hydrogen within the cell or that this bacterium has developed a compensatory mechanism which prevents molecular hydrogen from affecting its nitrogen fixation (240).

Cellulosic materials like filter paper and dry leaf, when mixed with soil, result in an increase in total nitrogen (78). When small amounts of molasses are added the cellulosic substances undergo oxidation more readily, and there is a greater fixation of atmospheric nitrogen (77). Nitrogen fixation also takes place when sodium salts of organic acids are allowed to oxidize in air on the soil surface (78). Addition of 125 to 500 mg. of ascorbic acid to a 100 ml. culture of *Azotobacter* in an invert sugar solution increases the intensity of nitrogen fixation 26 to 33 per cent (98).

Temporary stimulation of the total soil population of bacteria, fungi and actinomyces follows disinfection (272). Hexachlorobenzene at the concentration ordinarily used has a slightly stimulatory effect on *Azotobacter* and nitrite-forming organisms, but almost no action on *Cytophaga,* actinomyces and nitrifying or ammonifying organisms (227).

VI. OTHER INHIBITORS OF NITROGEN FIXATION AND NITRIFICATION

1. CARBON MONOXIDE, HYDROGEN. The common sensitivity of the nitrogen-fixing mechanisms of leguminous plants, *Azotobacter* and *Noctoc muscorum* to carbon monoxide or hydrogen inhibition suggests that nitrogen fixation is similar in the different groups of aerobic organisms (323).

Hydrogen acts as a specific inhibitor of nitrogen fixation in three species of *Azotobacter* and of symbiotic fixation in red clover (328), inhibition depending upon the nitrogen as well as the hydrogen concentration (320). The inhibitory action of molecular hydrogen on *Azotobacter* is reversible and competitive (329). The toxic effect of hydrogen ions on soil bacteria is related to the high adsorbability of the ion, probably becoming toxic by its strong competition for adsorption sites (187).

Hydrogenase activity is inhibited by urethane (221), sodium azide and cyanide (168). A concentration of M/1000 potassium cyanide suppresses the oxidation of hydrogen by *A. vinelandii* (315). The effect of carbon monoxide is comparable, while sodium azide, sodium iodoacetic acid and sodium fluoride inhibit respiration more than oxidation of hydrogen (315). Ammonium salts which completely inhibit nitrogen fixation by *Azotobacter* reduce the hydrogenase content 65 to 85 per cent (169). Exposure of *Nitrobacter* to free ammonia for several years does not kill the cells but poisons the nitrite oxidation mechanism (29). Reducing substances in concentration suppress *Azotobacter,* which does not develop under anaerobic conditions (232). Ethylurethane hinders nitrogen fixation by *Azotobacter* by blocking the active bacterial surface concerned with fixation (90).

2. MUTAGENIC INFLUENCES, EXCRETIONS. *Azotobacter* subjected to mutagenic influences produces strains which fail to fix nitrogen, but reverse mutations occur and can be accelerated by exposure to ultraviolet light (330).

Deleterious as well as beneficial effects may result from excretions in mixed cropping (328). Dominant bacteria on root surfaces are sensitive to the type of plant and stage of root development (57). Of 17 amino acids used experimentally, only phenylalanine and D-argenine materially retarded nitrogen fixation by *A. chroococcum,* but only phenylalanine occurs in sufficient quantities in soils to exert an inhibitory action (118).

The organic soil fraction soluble in petroleum ether inhibits *Rhizobium* spp. (52).

3. ANTISEPTICS, HERBICIDES. Sodium diethyldithiocarbamate poisons soil nitrification (171). Addition of 2,4-D to silt loam and sandy loam at rates of 100 p.p.m. or application of 500 p.p.m. to sandy soil has no significant effect on total plate counts of fungi, actinomyces or Protozoans in either soil, but in both soils *Nitrosomonas* and *Nitrobacter* are greatly decreased by 2,4-D in a concentration of 100 p.p.m. (249). Recovery is generally complete in 20 days (259).

4. BACTERIOPHAGE. The fatigue of alfalfa soils in France is ascribed to the presence of a bacteriophage for the root nodule organism (70). Observations on soil and plant samples from 29 irrigated alfalfa fields revealed bacteriophage in eight soils with alfalfa three years old or more and in the root tissues of the three-year-old alfalfa in one field (286). Nodulation on affected plants was poor, and all nodules tested yielded bacteriophage (286). In a later study phage was found in every alfalfa field tested and in 58 of the 62 samples taken, but there was no apparent correlation between phage incidence and the age of alfalfa stand, soil type or soil reaction between the pH limits of 5.26 and 7.39 (155). The lytic agent was isolated in only one instance from a soil not bearing legumes (155). Bacteriophage for nodule bacteria, however, frequently exists only on the surface of the nodules, and clover plants with the phage are vigorous and normal (82). One strain of phage lysed only nodule bacteria from clover, while another lysed, in addition, the nodule bacteria of peas, vetch and lentils (82). A bacteriophage against ammonifying bacteria caused total lysis under laboratory conditions (24). Bacteriophage adsorption diminishes and its effect on cultures increases with soil humidity up to 80 per cent of the total moisture capacity and decreases with diminishing

soil pH when introduced at pH 8.7 (160). Saturation with ferric or hydrogen ions inactivates both the bacteriophage and the bacterial culture introduced simultaneously (160).

Of 26 unidentified strains of aerobic spore-forming bacteria, nine caused the inactivation and two the lysis of *Rhizobium meliloti* phage (53).

VII. SOIL AND PLANT NITROGEN IN RELATION TO GROWTH

In agricultural soils the nitrogen as nitrates may amount to as much as 300 p.p.m. of moist soil (207). The yields of staple crops in India suffer when soil nitrogen becomes as low as 300 to 700 p.p.m. (198). Peach trees make satisfactory growth only when the nitrogen content of the nutrient solution is maintained at 60 or more p.p.m. (62). The green weight of peach and apple trees is much less with minimum levels of nitrogen than with low levels of either phosphorus or potassium (62).

On the other hand, 70 spermatophyte species survive in gypsum sand having a concentration of total nitrites and nitrates of only eight p.p.m. (88, 251). Leaves of sweet potato plants receiving ten p.p.m. nitrogen are light green, but few are shed (174). In rooted, leafy citrus cuttings supplied with nitrogen as potassium nitrate in culture solution, growth at three and five p.p.m. is greater than at one and two p.p.m. and less than at the higher concentrations of ten and 15 p.p.m. nitrate (124). The plant requirement for nitrogen may be small, a concentration of nitrites or nitrates in the atmosphere or cell sap equivalent to one part nitrogen to 120,000,000 parts water ordinarily supplying a sufficient quantity for assimilative purposes (200).

In nutrient solutions used for experimental work not concerned with nitrogen deficiencies, a total concentration of nitrogen of approximately 55 p.p.m. is frequently maintained in the form of nitrates or ammonia or the two combined (132, 255). Plants which take up nitrogen exclusively as ammonium salts generally contain very distinctly higher percentages of nitrogen than plants supplied with nitrates (253, 229). This observation has been substantiated for sugar cane (215), corn (183) and tomato (274). The more alkaline the nutrient solution, the more rapid the absorption of nitrogen from ammonium salts (197). In apple trees maintained at low temperatures and having an abundant carbohydrate

reserve there is a much more rapid synthesis of organic nitrogen from ammonium salts and a much more rapid increase in volume of the plant than in comparable cultures supplied with nitrate (208). In cotton plants under conditions favorable for carbohydrate formation, ammonia is much more readily converted into organic nitrogen than is nitrate (133). Detoxication of free ammonia within lupine seedlings is accomplished by the formation of asparagine or glutamine in the presence of abundant carbohydrate reserves (44).

The nitrate content of sugar beet petioles reaches a maximum in late May or early June and decreases to near zero at harvest, varying directly with nitrogen content within the limits normally present in these soils (284). The earlier in the growing season that soil nitrate drops below 1000 p.p.m. and the more days it remains below this level, the smaller the yield and the higher the sucrose concentration (284). The percentages of nitrogen under various fertilizer treatments are more than four times as high in the leaves as in the beets (131). Sugar beets grown in nitrogen deficient sand cultures with an excess of potassium contain 0.90 mg. of ammonia per 100 gm. of leaves, while with a surplus of nitrogen and a deficiency of potassium the ammonia content amounts to 29.4 mg. per 100 gm. of leaves (85). The nitrogen percentage content of peas on a dry weight basis ranges from 3.91 at a soil pH of 5.3 to 4.17 at a soil pH of 7.5 (280). The nitrogen content of potato leaves on a dry weight basis varies from 2.75 to 3.25 per cent in untreated soils to 4.50 to 5.25 per cent in soils given different fertilizer treatments, including various combinations of nitrate, phosphorus and potassium (21). The protein nitrogen level in barley leaves varies from 3.23 per cent in the youngest leaves to 4.06 per cent in mature and 2.52 per cent in the oldest leaves (227). The decrease in concentration in the older leaves may result in part from dilution of the protein by increasing amounts of cellulose and other inert materials (30). This decrease no doubt also reflects withdrawal of water-soluble nitrogen to more actively growing centers (30), particularly in the nitrogen deficient plant. Over a period of 20 days nitrogen in the fourth leaf of nitrogen deficient barley plants, expressed as a percentage of dry weight, dropped from 1.82 to 0.19, a decrease to nearly one-tenth (305). These leaves are, however, entirely capable of protein synthesis, since when nitrogen is sup-

plied protein is rapidly synthesized (305). Similar results have been obtained with cotton (222). The total nitrogen content of mature leaves from dicotyledons growing in gypsum sand having a maximum concentration of nitrite and nitrate of eight p.p.m. ranged from 1.25 to 4 per cent of the dry leaf weight (252).

Since comparative nitrogen recoveries in crops are not markedly different upon application of 40 pounds and 80 pounds of nitrogen per acre (225), fertilizer treatments may often supply an excess of nitrogen. Of the total nitrogen present in forest soils, 90 to 95 per cent is unavailable as heterocyclic polyoxy compounds of high molecular weight, the lignin-protein complexes (269).

Recorded bacterial activity often can not keep pace with nitrogen losses by leaching and cropping (140). Soil nitrogen depletion by these means or otherwise may be twice as great as that utilized by plants (75, 179). Ammonium nitrate decomposes rapidly to molecular nitrogen and water in sunlight and more slowly in the dark (75). In a three-inch soil layer exposed to the weather for 78 weeks, however, ammonium nitrogen increased much more rapidly than nitrate nitrogen, and organic nitrogen not at all, pointing to the conclusion that replenishment of soil nitrogen may possibly occur through adsorption of atmospheric ammonia (140).

The entire *Azotobacter* inoculation problem apparently hinges upon conditions in the soil inoculated. In general, no significant effects of inoculation with commercial nitrogen-fixing bacterial cultures, as Azotogen, Legumin and Radicin, on dry weight, nitrogen content of plants or yields have been observed (10, 275, 248, 249). There is no evidence that maintenance of *Azotobacter* in a soil for a period of 20 days influences either the crop or the soil nitrogen balance (110). Soil inoculation with *Azotobacter* has no effect on yield in sand cultures of corn (264). The presence of other bacteria may prevent *Azotobacter* growth in the vicinity of root hairs, however (264). It is possible that the excretion products of root hairs have to be changed by other bacteria before being utilized by *Azotobacter* (264).

Root nodule bacteria were found to fix 67 pounds of nitrogen per acre from August to the following June, an amount equivalent to the nitrogen contained in approximately 420 pounds of sodium nitrate (67). Yet, following a legume crop certain soils often contain less nitrogen than the next crop will require (276). Maxi-

mum dry weight yields of soybeans are obtained when applications of readily available combined nitrogen are made rather than when plants develop mainly on nodule nitrogen (212). Under conditions favorable for rapid growth, urea nitrogen increases soybean yields but has little effect upon total plant nitrogen content (224).

VIII. EFFECTS OF CARBOHYDRATE AND NITROGENOUS COMPOUNDS ON NITROGEN FIXATION AND NITRIFICATION

While crop yields are probably more directly related to the supply of available soil nitrogen than to any other single factor, the nitrogen cycle is dependent upon and dominated by the carbon cycle (211). Legume root inoculation occurs only if the internal ratio of carbohydrates to soluble nitrogen is not extreme (318, 181). Nodules develop only where enough carbohydrate is present to allow at least moderate root growth (7). Decreased nodulation in the presence of soluble nitrogenous salts results from inadequate carbohydrate in the roots, since where nitrogen is abundant carbohydrate is used for growth in above-ground parts where it is synthesized (8). The inhibitory effects of combined nitrogen upon nodule production by inoculated red clover plants can be partially overcome by supplying additional carbon dioxide to increase carbohydrate synthesis in the plant (111). High carbohydrate favors a wide distribution of nodules over the root system rather than their localization near the upper portions of main roots characteristic of plants with a low carbohydrate level (8). As the carbohydrate : nitrogen ratio narrows under a restricted carbohydrate supply, as commonly occurs in old nodules, the host tissues are parasitized, true symbiosis existing only under conditions of readily available carbohydrate (273). An extremely high carbohydrate : nitrogen ratio in the plant, however, inhibits nitrogen fixation as does an extremely low ratio (214), fixation by symbiotic bacteria being a function of the richness in mineral nitrogen of the medium and the activity of the inoculating bacteria (71). Inoculated soybeans grown in nitrogen-free sand under normal high light intensity form numerous large nodules but fail to fix atmospheric nitrogen (214).

A single crop of soybeans may fix up to 165 pounds of nitrogen per acre, an amount increased somewhat by straw (224) applied under the proper conditions and at an appropriate time. In green-

house experiments straw added at planting time or six weeks earlier decreases the yields of inoculated soybeans (224) unless the nitrogen supply is such as to maintain a carbohydrate: nitrogen ratio not greater than 20: 1 (247).

When calcium nitrate enriched with N^{15} is added to soil in the presence of oat straw it is first immobilized by microorganisms, and its mineralization follows subsequently (40). Nitrogen of green manure, inactivated by carbon, results in the formation of nitric acid, and is only slowly released to subsequent crops (225). As the decomposition of plant materials proceeds and the carbon content decreases, the amount of soil nitrogen also decreases materially, though not to the same extent as the carbon (217). The rate of cellulose decomposition in the soil increases with increase in available nitrogen until nitrogen is present in amounts necessary for optimum growth, a point reached when the ratio of nitrogen: cellulose is about 1: 35 (12). With lower amounts of nitrogen the cellulose fermenters reduce nitrate as rapidly as formed (12).

The carbohydrate: nitrogen ratio in the soil is a factor exerting an influence on nitrification as profound as that of soil reaction, which to a large extent explains the less complete utilization of barnyard manure nitrogen as compared to nitrogen in artificial fertilizers (143). The rate of soil nitrification is retarded if the carbohydrate: nitrogen ratio is greater than 20: 1 and is influenced by the composition of the organic matter, the rate at which it is decomposed, and by the nature and solubility of the nitrogen source (247). In soils high in carbohydrate poor plant growth results from lack of nitrate, not from direct inhibition by carbohydrates (12). Nitrogen may be retained in the soil by a heterotrophic population which sometimes builds up quickly as where glucose is percolated through soil having a mineral source of nitrogen (172). When the supply of carbohydrate is exhausted and the population begins to decline, ammonia is produced through lysis of dead cells, and some of the immobilized nitrogen is again released (172).

Application of molasses to the nitrogen-deficient soils of India increases soil nitrogen and crop yield (77). Anaerobic fermentation of the molasses before application to the soil results in a nearly three-fold increase in nitrogen-fixing ability compared with unfermented molasses (25). The molecular nitrogen fixed after application of five tons of fermented molasses per acre, however, is

equivalent to only 200 pounds of ammonium sulfate (25). Under other conditions large applications of molasses may arrest nitrification, causing conversion of ammonium compounds into organic nitrogen (61).

Nitrification is weaker in conifer than in mixed forests, though the water-soluble substances of autumn leaf fall have a depressing effect on nitrification (254). Various organic substances which are supposed to inhibit nitrification in culture do not markedly inhibit oxidative nitrification in soil, even at a concentration of 0.1 per cent (171). Lignin functions in the preservation of nitrogen by acting as a buffer for the absorption of ammonia and functioning in the direct fixation of some of the protein in lignoprotein complexes (301). Fixation of ammonia by lignin occurs through simultaneous oxidation and nitrogen fixation by way of the phenolic hydroxyl groups of lignin (22). Lignin fixes nitrogen in an acid medium, while nitrogen fixation by cellulose requires a basic medium (159). Sawdust has little value as a soil improver and may cause nitrogen deficiencies in succeeding crops, especially vegetables, for a considerable time (306), apparently providing a substrate for a bacterial flora which immobilizes the essential nutrients.

The reduction of nitrates and nitrites by soil bacteria is effected most rapidly where the carbohydrate: nitrogen ratio is low (14).

IX. NITROGEN SOURCES OF MICROORGANISMS

Azotobacter chroococcum uses combined in preference to atmospheric nitrogen, but in the presence of plant material the growth, consequently the nitrogen requirement, is so greatly increased that this species also utilizes nitrogen of the air (335). Little or no nitrogen fixation occurs in a culture medium containing ammonium salts, but in most soils nitrogen fixation by *Azotobacter* is not markedly retarded by the presence of nitrogenous materials (136). Of 35 organic compounds tested as nitrogen sources for *Azotobacter* grown in the absence or nitrogen gas, only urea, asparagine, aspartic acid, adenine and glutamic acid were definitely assimilated (136). Only urea was as readily utilized as ammonium salts, nitrites or nitrates (136). It appears that *A. chroococcum* utilizes the inorganic nitrogen by-products formed in cellulose decomposition by *Sporochaeta cytophaga,* leaving the medium more acid in the presence of ammonium sulfate and more basic in a nitrate

medium (258). Twice as much nitrogen is fixed in soil aerated with nitrogen gas free from ammonia as in soil lots aerated with ammonia gas, indicating that anaerobic nitrogen fixers are more active than aerobic under the conditions investigated (282).

There is no selective action in the fixation of N^{14} and N^{15} atoms by *A. vinelandii* (41). *Nostoc muscorum, A. vinelandii, Cl. pasteurianum* and inoculated red clover plants assimilate 100 to 1000 times the quantity of molecular N^{15} necessary for detection (47).

Since only the ammonia nitrogen of manure undergoes nitrification, there is no trace of nitrification following the distillation of manure (16). As shown by the following table, nitrification of cottonseed meal and ammonium sulfate is decidedly accelerated by calcium carbonate (326).

TABLE I

NITRIFICATION IN SOILS (326)

	Nitric nitrogen in mg. produced per 100 gm. of soil in three weeks	
	Alone	With $CaCO_3$
Pasture soil		
Ammonium sulfate	7.2	57.2
Cottonseed meal	32.4	43.6
Garden soil		
Ammonium sulfate	0.2	15.8
Cottonseed meal	17.3	41.5
Sandy soil		
Ammonium sulfate	0.0	0.0
Cottonseed meal	0.0	0.0

In setting up the above experiment, each 500-gm. soil sample was mixed intimately with the quantity of cottonseed meal or ammonium sulfate containing 0.3 gm. of nitrogen (326). Some soils in the presence of calcium carbonate nitrify ammonium sulfate to a greater extent than cottonseed meal, while other nitrify cottonseed meal more readily (326). Two factors influencing nitrification are probably the inhibitory action on nitrifying organisms of ammonium sulfate and of the acids formed in the absence of bases to neutralize them (326). Also, different soils may contain different classes of nitrifying organisms, some of which oxidize ammonium salts more rapidly, while others prefer organic materials (326).

Bacillus pyocyaneus and *B. liquefaciens* are denitrifying bacteria

which may develop at the expense of nitrates without other nitrogen sources, but certain other denitrifying species require ammonia in addition to nitrates (161, 162).

X. RELATIONS OF MOISTURE TO SOIL NITROGEN

Maximum nitrification in a number of soils of temperate areas varying from loose sand to tight clay occurs at a moisture content ranging from 50 or 60 per cent (116) to 70 or 80 per cent of the moisture-holding capacity (116, 130). Nitrification in one type of tropical soil is highest at 77 inches of rainfall annually and lowest at 163 to 180 inches (41). In the Philippine Islands the highest nitrate content coincides with the period of moderate soil moisture and the lowest with the time of lowest moisture content (283). Rainfall carries soil nitrates downward in everglades peat, considerably reducing their accumulation by the end of the rainy season (204). Normally, however, the onset of rains marks the rise of nitrates on a bare soil and the drop under mulch (122). Air drying causes rapid conversion of ammoniacal to nitrate nitrogen, increasing the nitrifying, ammonifying and nitrogen-fixing abilities of the soil (158).

According to plate counts on 52 soils, *Azotobacter* spp. are usually present in irrigated lands but absent from non-irrigated soils in rainfall belts of less than ten inches and only infrequently present in rainfall belts of 15 to 20 inches (285). Yet resistance to desiccation is evident in *A. chroococcum* cultures dried on dextrine agar and kept in this condition for ten years, but appearing normal after a few transfers and fixing only 16 per cent less nitrogen than control cultures (213). The competition between soil and microorganisms for water is influenced by mineral colloids, as clay, which affect the organisms through adsorption and diffusion of their soluble products (69).

XI. EFFECTS OF SEASONAL INFLUENCES AND TEMPERATURE ON THE NITROGEN CYCLE

In French soil and subsoil of five types ammonification and nitrification reach maxima in autumn, denitrification is most rapid in winter, and nitrogen fixation does not vary greatly with the time of year (289). Where differences in seasons are more pronounced, however, most nitrates accumulate in summer and least in winter

(18). Under the climatic conditions in Arkansas appreciable amounts of nitrates are produced in soils during fall and winter, but in the absence of cover crops most of these nitrates are lost from the soil before spring (17). Humidity of 40 to 70 per cent and temperatures of 34 to 38° C. are optima for nitrate accumulation in sandy desert soils (334). The presence of nitrite in a brackish lagoon is detectible only during the winter months of November to February, which probably indicates that in other seasons the change from ammonia to nitrate occurs too rapidly for accumulation of the intermediate stage (50).

In warmer climates the optimum temperature for nitrogen fixation by *Azotobacter* strains is between 35 and 40° C. as opposed to 28° C. in temperate areas (121, 76). There is hardly any ammonia formation by *Azotobacter* below 10° C. or above 60° C. (76), which would indicate that aerobic biological fixation occurs chiefly during warm months when inorganic nitrogen is continuously being removed by vegetation, while during the colder months it leaches to somewhat lower levels or is lost by volatilization. The greatest numbers of microorganisms at the end of 24 months of storage occur in soil maintained at 10° C. and fewest at 40° C. Storage at 10° C. for 24 months, however, greatly reduces the nitrogen-fixing capacity of soils compared with similar soils stored at 20° C. and 30° C. (119). Seasonal changes and the accompanying temperature fluctuations are also most important in controlling the nitrifying bacterial activity in soils (18).

XII. NITROGEN LOSSES FROM THE SOIL

It was estimated in 1930 that more than 23 million tons of nitrogen are being lost annually from soils in the United States through harvested crops, grazing, erosion and leaching, while only slightly more than 16 million tons are being returned through fertilizers, rainfall, irrigation waters, plant residues and fixed nitrogen, leaving an annual deficit of more than six and a half million tons (179). A more recent estimate assumes an annual loss of ten million tons of nitrogen from agricultural soils in this country, a figure equivalent to more than 30 times the amount of nitrogen supplied by chemical fertilizers (30).

Fixed nitrogen leached from the soil is carried away in runoff or soil water and is contributed to the ocean (30). Marine organisms

seem to depend mainly on this source of fixed nitrogen, since the ocean appears to support little nitrogen fixation (333, 30). Available nitrogen often limits the productivity of the sea (333). Much of the nitrogen contained in human food crops passes ultimately into sewage and is contributed to drainage water (30).

Other smaller losses of fixed nitrogen are due to denitrifying microorganisms, principally anaerobes which reduce nitrate to molecular nitrogen (30). Man also accomplishes significant amounts of denitrification in the combustion of explosives such as nitroglycerine and trinitrotoluene in which the oxygen of the nitro group is used as hydrogen acceptor for the combustion of reduced organic compounds (30).

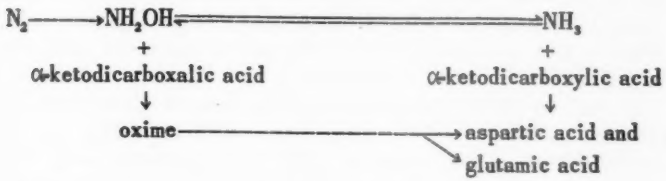
XIII. MECHANICS OF AEROBIC NITROGEN FIXATION

Studies of the enzyme systems involved as well as experiments with N^{15} as a tracer indicate that ammonia is the most probable key intermediate in nitrogen fixation by *Azotobacter* (46, 324), a view supported by the preference of *A. vinelandii* for ammonia rather than nitrate when supplied with ammonium nitrate (49). Thus *Azotobacter* fixes nitrogen by combination with hydrogen instead of oxygen (307). This makes the biological process more efficient than electrochemical fixation from the energy standpoint (307). The energy efficiency of nitrogen fixation has been estimated to be the same as in fermenting glucose, which disproves the theory that only carbon-linked hydrogen participates in the hydrogen transitions of nitrogen fixation by *Azotobacter* (94).

It has been postulated that the endothermic reactions of nitrogen fixation by *Azotobacter* are promoted by a catalyst which is not the respiratory enzyme (321, 92), its structure including COOH, NH_2 and C:O groups (92). The active group in nitrogen fixation is believed to be R—CH—NH_2—?—$COCOCO_2H$, possibly diketoaminoglutamic acid, which is bound to a protein or a colloidal carrier exchanged in the process of fixation (99). This fixation is believed to consist of addition of nitrogen across the two C:O groups, followed by reduction of active hydrogen furnished by the dehydrase system, in the course of which the protein moiety is changed to one with a lower oxidation potential, and the nitrogen adduct is altered to —$C(ONHNH_2):C(OH)CO_2H$, which then proceeds to —$C(OH):C(OH)CO_2H$ and $RC(CO_2H)$; the latter

interacts with keto acids in the presence of dehydrase, yielding amino acids and water (99). This scheme would explain the positive action of oxygen, hydrogen peroxide, boric acid, molybdic acid and oxidizing agents in general as well as the repressing action of hydrogen, hydroquinone, hydrogen sulfide, aldehydes and reducing agents (99). Surface-active agents block the surface between the active group and the protein, retarding the reaction (99).

It has been proposed that nitrogen fixation in legume nodules follows the scheme (295):



This theory is supported by the occurrence of nitrogen in these legumes in early growth almost exclusively in the form of α-amino nitrogen which is almost entirely aspartic acid, but with demonstrable amounts of glutamic acid in peas (295). The approximately 100 per cent inhibition produced by a 10^{-2} molar concentration of NH_2OH, however, does not favor the conclusion that it is an intermediate in nitrogen fixation (220). Hydroxylamine, which is highly toxic, can not be used as a nitrogen source of either *Azotobacter* or legumes (30). Hydroxylamine has been reported to appear transiently under alkaline conditions and more permanently in an acid medium in the bacterial oxidation of ammonia (59), however, and non-nitrogen fixing *Aspergillus* and a number of higher plants also form hydroxylamine (30).

It is not known whether the respiratory enzyme hydrogenase in *Azotobacter* and the readily oxidized or reduced hemoglobin compounds in legume nodules are associated with nitrogen fixation. In *Azotobacter* sugar utilization in respiration and nitrogen fixation shows differential reactions to boric acid, aliphatic acids and alcohols (96). The source of energy for *Azotobacter* in nitrogen fixation, however, is the decomposition products of sugar, not the sugar itself (307). Certain substances which repress respiration in *Azotobacter* have little effect upon or stimulate fixation (96).

Similarities among the proposed nitrogen-fixing mechanisms of different aerobic bacteria include the reaction with keto acids (99) and the production of ammonia and possibly hydroxylamine as intermediate products (92, 295).

XIV. SUMMARY

The survival of many vascular plants on what have been designated as essentially nitrogen-free substrates (88, 243, 251), the failure of recorded bacterial activity to keep pace with the soil nitrogen losses from leaching and cropping (140), and the existence of non-nitrifying agricultural soils (266) appear to justify the refocusing of certain facts relevant to the nitrogen sources and minimum nitrogen requirements of seed plants.

In addition to the traditional biological sources of plant nitrogen, nitrification on a large scale occurs as a result of oxidation at the surfaces of acidoid soil particles (230), a phenomenon accelerated by tillage (69) and possibly also by perfusing the soil with water. In nature nitrites oxidize readily to nitrates in the absence of bacterial action (230). Varying amounts of nitrous oxides, ammoniacal nitrogen and other forms of nitrogen in dust particles are returned to the soil in rain and snow (242, 200, 313, 241, 144, 30).

Symbiosis between nitrogen-fixing bacteria, including *Bacillus planticola rubescens* (243) and *Actinomyces alni* (226), and certain non-leguminous species of seed plants may be a widespread phenomenon (234, 262, 201, 226, 243, 245, 246), and a number of non-legumes are believed to assimilate atmospheric nitrogen symbiotically or by some other means when this element is not available in any other form (178, 149, 203, 243, 245, 246).

Physical and mechanical conditions of the soil, particularly pH (311), determine which of the saprophytic nitrogen-fixing genera, *Azotobacter* or *Clostridium*, predominates (54). *Azotobacter* (28), certain blue-green algae (103) and most nitrifying bacteria (325) are favored by a well aerated, slightly alkaline soil, while with moderate acidity the nitrogen-fixing organisms are chiefly *Clostridium* spp. (311) and symbionts (127). The tropical genera *Azotomonas* (263) and *Beijerinckia* (72) as well as *Rhodospirillum rubrum* (113), *Chlorobacterium*, *Chromobacterium* (177) and certain strains of *Aerobacter aerogenes* (257) are also capable of fixing atmospheric nitrogen, which may or may not be quantitatively significant to agriculture.

The practical value of nitrogen fixed in large amounts by *Nostoc* (48), *Anabaena* (267), a number of other blue-green algae (268) and by fungi other than certain bacterial genera remains to be evaluated. *Serratia marcescens, Bacillus subtilis* and *Aerobacter aerogenes* are known to convert insoluble nitrogen compounds to a soluble form (26, 27).

The effects of carbon dioxide and other root excretions of different crop plants on the nitrogen-fixing soil microflora are variable but not marked. The root excretions of chick pea benefit associated wheat plants most when the ratio of wheat to chick pea plants is 2: 1, though the beneficial effect of the association on the growth of wheat is neither marked nor constant (188), possibly in part because the conditions which favor excretion discourage plant growth (30) or because only 28.7 per cent of the nitrogen lost from certain soils is in the harvested crop, leaving 71.3 per cent unaccounted for (36). Soil nitrogen is sometimes immobilized or exhausted by a zymogenous soil microflora (239), and varying amounts are leached or lost by volatilization.

Nitrate nitrogen (56), moisture content and numbers of bacteria are highest at all seasons in fallow land and lowest in sod (205). Fluctuations in nitrate nitrogen often do not correspond closely to variations in numbers of bacteria, fungi or actinomyces (205) believed to be active in nitrification or nitrogen fixation, possibly because nitrate may accumulate by physicochemical means, various crops remove different amounts of nitrogen, and losses by volatilization and leaching vary from one soil to another.

The stimulatory effect of soil Protozoans (65, 100, 129) and certain green algae, as *Chroococcum, Pleurococcus* and *Chlorella* (308), on *Azotobacter* is indirect and limited (267). A number of soil bacteria have been demonstrated to have an inhibitory action (51, 206, 298) or accelerating effect (145, 176) on nitrogen fixation by certain saprophytes. Competition exists among different strains of nodule bacteria (291), and large numbers of *A. chroococcum* prove harmful to lucerne or white clover in sand culture (146).

Aerobic saprophytic bacteria fix nitrogen only in alkaline soils (163), having a growth and activity optimum usually between pH 7 and 9 (166). Soil acidity favors nitrogen fixation by soybeans (127) and clover (145). The pH values of nodules of legume species examined were found to be within the narrow range of 5.5

to 6.6 (317). Aerobic nitrifiers in acid forest soils having a pH value as low as 4.7 are largely actinomyces (142). Anaerobes in certain Iowa soils appear to assume an important role in nitrogen fixation, particularly at an acid pH (311). While bacterial nitrification may occur at a pH as low as 2.9 (238), and physicochemical nitrification is most marked in acid soils (230), there is a higher degree of nitrification in soils having more nearly neutral reactions (325).

The effect of the addition of any particular element on organisms important in the nitrogen cycle depends upon whether that element is otherwise deficient or present in excess and, to some extent, upon the soil reaction. Ordinarily phosphorus (19, 236, 216), calcium (235, 3, 39, 186, 126) and potassium (228, 227) fertilization in appropriate amounts favorably influences development and nitrogen fixation by *Azotobacter* spp. and legume bacteria. Saprophytic nitrogen fixation in certain western soils increases with the accumulation of plant residues, leaching of alkali and the addition of the following elements, listed in order of decreasing action: $Na > Ca > Fe > Mg > Mn > K$ (117). The order of importance of elements as nutrient for legume bacteria appears to be $Ca > Mg > Ba > K > H$ (186). The effects of toxic ions, as copper and zinc, on soil nitrification are less in organic than in mineral soils (173), apparently from the adsorption of such metals on colloidal surfaces. Though heavy metals retard nitrogen fixation by *Azotobacter agile,* presumably by reaction with the COOH group of the catalyst, many compounds which react with the basic group of the catalyst exert a stimulatory action (93). Traces of molybdenum accelerate growth and nitrogen fixation by *Anabaena, Nostoc* (32), *Azotobacter* (288, 181, 42, 135), *Clostridium butyricum* (148) and root nodule bacteria (290). Microquantities of radium and certain other radioactive elements improve nodulation and nitrogen fixation in pea roots (83). A hemoglobin-like pigment existing in leguminous root nodules in two or more forms interconvertible by oxidation and reduction may be associated with symbiotic nitrogen fixation (294), though possibly the same conditions favor both pigment formation and nitrogen fixation. Hydrogenase content is correlated with nitrogen fixation by a number of *Azotobacter* spp. (314). That the oxidation and nitrogen-fixation mechanisms might be linked is suggested by the function of the

oxygen-carrying pigment in legume nodules and the activity of hydrogenase in nitrogen fixation by aerobic soil bacteria and possibly by glue-green algae. The rate and extent of nitrogen fixation by *Clostridium pasteurianum* have been increased two- to three-fold by the removal of carbon dioxide during fermentation and through the use of shaken cultures (240), possibly in the same way that biological processes are activated by tillage, since in clay and similar soils hydrogen and nitrate ions at neighboring points are irregularly distributed (69). Molecular hydrogen inhibits nitrogen fixation by aerobic agents, but not by *Cl. pasteurianum* (240). The toxic effect of hydrogen on many soil bacteria (328) is related to the high adsorbability of the ion and its competition for adsorption sites (187). Carbon monoxide (323) and potassium cyanide inhibit nitrogen fixation by suppressing the oxidation of hydrogen (315).

Deleterious as well as beneficial effects may result from excretions in mixed cropping (328). Soil disinfection temporarily stimulates the total population of bacteria, fungi and actinomyces (272), while the effects of herbicides are transient, varying from slight acceleration to slight inhibition (259, 227, 172). A bacteriophage for the root nodule organisms, often present in alfalfa or other legume soils (286, 155), frequently exists only on the nodule surface, and clover plants with the phage are vigorous and normal (82).

The nitrate content of sugar beet petioles varies directly with soil nitrogen within the limits normally present in sugar beet soils (284). The earlier in the growing season that the concentration of soil nitrate falls below 1000 p.p.m. and the more days it remains below this level, the lower is the yield and the higher the concentration of sucrose in the beets (284). The percentages of nitrogen under various fertilizer treatments are more than four times as high in the leaves as in the beets (131). Total nitrogen content of mature angiosperm leaves ordinarily ranges from around 2.5 to 5.0 per cent of the dry weight, varying with age of the leaf (327), soil pH (280) and fertilizer treatment of the soil (21). Leaves of dicotyledons growing in a nitrogen deficient gypsum sand deposit ranged from approximately 1.5 to 4.0 per cent total nitrogen on a dry weight basis (252).

In normal agricultural land the nitrogen as nitrates may amount to as much as 300 p.p.m. of moist soil (207). The yield of staple

crops in India suffers when soil nitrogen becomes as low as 300 to 700 p.p.m. (198), possibly because of the large amounts of carbohydrate material in the soil. Peach and apple trees make satisfactory growth where soil nitrogen is present in a concentration of 60 p.p.m. (62). Sweet potato plants survive with ten p.p.m. nitrogen supplied as nitrate (174). In rooted citrus cuttings transferred to nutrient solution, growth increases with concentration of nitrate in a series of one, three, five, ten and 15 p.p.m. (124). In certain species of vascular plants a concentration in the atmosphere or cell sap equivalent to one part nitrite or nitrate to 120,000,000 parts water ordinarily supplies sufficient nitrogen for assimilative purposes (200). In nutrient solutions used for experimental work not concerned specifically with nitrogen deficiencies, a total concentration of nitrogen of approximately 55 p.p.m. is sometimes maintained in the form of nitrates or ammonia or the two combined (132, 255). A number of plants which take up nitrogen as ammonium salts, including corn (168), sugar cane (215) and tomato (274), contain higher percentages of nitrogen than plants supplied with nitrates (253, 229). Fertilizer treatments often provide an excess of nitrogen (225). A soybean crop may fix up to 165 pounds of nitrogen per acre (224), but non-symbiotic microbiological fixation ranges from a few to 50 pounds of nitrogen annually per acre (30).

The carbohydrate: nitrogen ratio exerts an influence on nitrogen fixation as profound as that of soil reaction (143). Best symbiotic nitrogen fixation occurs with medium amounts of both carbohydrate and nitrogen (318), and host nodule tissues are parasitized as the carbohydrate: nitrogen ratio within the plant narrows under a restricted nitrogen supply (273). Saprophytic nitrogen fixation in soils is ordinarily inhibited if the carbohydrate: nitrogen ratio is greater than 20: 1 (247). Straw manuring is beneficial only when the nitrogen reserve is such as to maintain a carbohydrate: nitrogen ratio of not greater than 20: 1 (224). Similarly the stimulatory (77) or inhibitory (61) effects of the application of molasses on soil nitrification and nitrogen fixation depends upon whether an imbalance is produced in the nitrogen: carbohydrate ratio. An excess of soil carbohydrate serves as a substrate for the activity of a heterotrophic soil microflora which temporarily immobilizes nitrogen (172). When nitrogen is present in the soil in a ratio of less than one part nitrogen to 35 parts cellulose the cellulose fermenters reduce nitrate as fast as it is formed (12).

Decreased nodulation in the presence of soluble nitrogenous salts results from inadequate carbohydrate in the roots, since where nitrogen is abundant carbohydrate is used for growth in aboveground parts where it is synthesized (7). The reduction of nitrates and nitrites by soil bacteria is effected more readily where the carbohydrate: nitrogen ratio is low (14).

An estimated annual nitrogen deficit of six and a half million (179) to ten million tons (30) is occurring in agricultural soils of this country through harvested crops, grazing, erosion and leaching. Frequently the amount of nitrogen lost from the soil through the action of aeration and light is twice as great as that utilized by plants (75). Nitrogen losses vary with the cropping procedure on cultivated land (120).

Nitrification in a variety of soils of temperate areas reaches a maximum at a moisture content ranging from 50 to 80 per cent of the moisture-holding capacity (116, 130), while nitrification in certain tropical soils is highest at around 77 inches and lowest at 163 to 180 inches annual rainfall (41). *Azotobacter* is usually absent from non-irrigated soils in rainfall belts of less than ten inches and frequently present in rainfall belts of 15 to 20 inches (287), though mineral colloids influence the competition between the soil and microorganisms for water (69). Where the differences in seasons are pronounced, most nitrate accumulates in summer and least in winter (18), even though during warm months nitrate is continuously being removed by vegetation.

A number of organic nitrogen compounds can serve as nitrogen sources for *Azotobacter* (136) which uses combined in preference to atmospheric nitrogen, but in the presence of plant material the growth and consequently the nitrogen requirement are so greatly increased that the organism also utilizes nitrogen of the air (335). Experimentally some soils in the presence of calcium carbonate nitrify ammonium sulfate to a greater extent than cottonseed meal, while others nitrify cottonseed meal more readily (326).

Studies of the enzyme systems involved and experiments with N^{15} as a tracer indicate that ammonia is the most probable key intermediate in biological nitrogen fixation by *Azotobacter* (324). The endothermic reactions of nitrogen fixation by *Azotobacter* are promoted by a catalyst which is not the respiratory enzyme (321, 92) and which appears to include COOH, NH_2 and C:O groups (92). This catalyst is variously influenced by oxidizing, reducing

and surface-active agents (99). The common elements of the present proposed nitrogen-fixing mechanisms of *Azotobacter* and legume nodule bacteria are reactions involving keto acids (99, 295), the production of ammonia (46, 324) and possibly hydroxylamine as intermediate products (59, 92). The inhibitory effect of hydroxylamine, which in nitrogen fixation by *Azotobacter* is reported to appear more permanently under acid conditions (59), may be responsible in part for the pH sensitivity of this organism. The role of hydroxylamine in nitrogen fixation is questioned (220, 30).

The common sensitivity of the nitrogen-fixing mechanisms of symbiotic and saprophytic aerobes and the blue-gree algae to such inhibitors as carbon monoxide and hydrogen (323) suggest that the mechanisms of nitrogen fixation are similar in all these organisms.

LITERATURE CITED

1. ALBRECHT, W. A. 1920. Symbiotic nitrogen fixation as influenced by nitrogen of the soil. Soil Sci. **9**: 275–319.
2. ———— and DAVIS, F. L. 1929. Physiological importance of calcium in legume inoculation. Bot. Gaz. **88**: 310–321.
3. ———— and HORNER, G. M. 1935. Nitrogen fixation in soybeans as influenced by exchangeable calcium. Trans. Third Int. Congr. Soil Sci. **1**: 140–144.
4. ALEEV, B. S. and MUDRETSOVA, K. A. 1937. Rol' fitoplanktona v dinamike azota v vode "svetuschago" vodeoma. Microbiologiia **6**: 329–338.
5. ALICANTE, M. M. 1935. Nitrification in acid soils. Philippine Jour. Sci. **58**: 162–169.
6. ALLEN, O. N. 1949. Experiments in soil bacteriology. 122 pp.
7. ALLISON, F. E. and LUDWIG, C. A. 1934. The cause of decreased nodule formation on legumes supplied with abundant combined nitrogen. Soil Sci. **37**: 431–443.
8. ————. 1935. Carbohydrate supply as a primary factor in legume symbiosis. Soil Sci. **39**: 123–143.
9. ————, HOOVER, S. R. and MINOR, F. W. 1942. Biochemical nitrogen fixation studies. IV. Experiments with excised legume nodules. Bot. Gaz. **104**: 63–71.
10. ————, GADDY, V. L., PINCK, L. A. and ARMIGER, W. H. 1947. *Azotobacter* inoculation of crops. II. Effect on crops under greenhouse conditions. Soil Sci. **64**: 489–497.
11. ANDERSON, A. J. and THOMAS, M. P. 1946. Plant responses to molybdenum as a fertilizer. I. Molybdenum and symbiotic nitrogen fixation. Australia, Coun. Sci., India Res., Bull. 198: 7–24.
12. ANDERSON, J. A. 1926. The influence of available nitrogen on the fermentation of cellulose in the soil. Soil Sci. **21**: 115–126.
13. Anonymous. 1925. Soil studies at the Wisconsin Experiment Station. Wis. Agr. Exp. Sta., Bull 373: 41–51.
14. BARRITT, N. W. 1931. The liberation of elementary nitrogen by bacteria. Biochem. Jour. **25**: 1965–1972.
15. BARTHEL, C. 1926. Kunna baljvaxbakterier i renkultur fixera atmosfäriskt kväve? Meddel. Centralanst. Försökväsendet Jordbruksomvad [Stockholm] **308**: 16.

16. ———— and BENGTSSON, N. 1926. Bidrag till frågan om stallgödselkvävets nitrifikation i akerjorden. 5. Meddel. Centrananst. Försoksvävs. Jordbruksomr. [Stockholm] **311:** 1–16.
17. BARTHOLOMEW, R. P. 1932. Activity of nitrification processes in the fall and winter months. Jour. Am. Soc. Agron. **24:** 435–442.
18. BATHAM, H. N. and NIGAM, L. S. 1930. Periodicity of the nitrate content of soils. Soil Sci. **29:** 181–190.
19. BAUMGARTEL, T. and BIHLER, C. 1930. Kritische Experimentalstudien zur Mikrobiologischen Bodenanalyse. (Ueber den Einfluss einseitiger Dauerdungung auf Vorkommen und Entwicklung von *Azotobacter chroococcum*). Landwirtsch. Jahrb. **71:** 855–876.
20. BEAR, F. E. and WORKMAN, A. C. 1919. The ammonia-fixing capacity of calcium sulfate. Soil Sci. **7:** 283–291.
21. BEESON, K. C. 1941. The mineral composition of crops with particular reference to the soils in which they were grown. U. S. Dept. Agr., Misc. Pub. 369.
22. BENNETT, E. 1949. Fixation of ammonia by lignin. Soil Sci. **68:** 399–400.
23. BERGE, H. 1949. Bodenbiologische Studien der Nachkriegszeit. Naturwiss. Rundschau **1949:** 73–75.
24. BERSHOVA, O. I. 1940. Dependence of the development of ammonifying bacteria on the bacteriophage in the soil. Mikrobiologichnii Zhurnal Akademiia Nauk URSR **7:** 97–117.
25. BHASKARAN, T. R. and PILLAI, S. C. 1937. Decomposition of cane molasses in soil and its bearing on soil fertility. Proc. Soc. Biol. Chemists [India] **2:** 33–34.
26. BHAT, J. V. and PALACHIOS, G. 1948. Studies on the influence of some bacterial cultures in the nitrogen status of the soil. Jour. Univ. Bombay **16:** 15–26.
27. ———— and ————. 1949. Studies on the influence of some bacterial cultures in the nitrogen status of soil. IV. The influence of *Aerobacter aerogenes* in the nitrogen status of soil. Jour. Univ. Bombay **17:** 84–87.
28. BLINKOV, G. N. 1948. Vliianie reackii sredi na intensivnost azotifixacii i rost azotobaktera. Mikrobiologiiâ **17:** 48–53.
29. BOMECKE, H. 1939. Beiträge zur Physiologie nitrofizierender Bakterien. Arch. Mikrobiol. **10:** 385–445.
30. BONNER, J. 1950. Plant Biochemistry. 491 pp.
31. BORTELS, H. 1933. Kurze Motiz über die Katalyse der biologischen Stickstoffbindung. Zentralbl. Bakt. II. Abt. **87:** 476–477.
32. ————. 1940. Über die Bedeutung des Molybdäns für stickstoffbindens Nostacaceen. Arch. Mikrobiol. **11:** 155–186.
33. BOSE, S. R. 1943. Fixation of atmospheric nitrogen by fungi. Sci. & Cult. **8:** 389.
34. BOSWELL, J. G. and GOVER, D. J. 1946. The microbiology of acid soils. 1. "Mor" bearing *Pinus sylvestris* and *Betula pubescens*. New Phytol. **45:** 218–224.
35. BRACKEN, A. F. 1940. Effect of various soil treatments on nitrates, soil moisture, and yield of winter wheat. Soil Sci. **50:** 175–188.
36. ———— and GREAVES, J. E. 1941. Losses of nitrogen and organic matter from dry-farm soils. Soil Sci. **51:** 1–15.
37. BRAY, R. H. 1945. Nitrate tests for soils and plant tissues. Soil Sci. **60:** 219–221.
38. BREED, R. S., MURRAY, E. G. D. and HITCHENS, A. P. 1948. Bergey's manual of determinative bacteriology. Sixth Ed. 1387 pp.
39. BRIOUX, C. and JOUIS, E. 1935. La nitrification dans les sols de limon des plateaux. Ann. Agron. **5:** 622–631.
40. BROADBENT, F. E. and NORMAN, A. G. 1947. Some factors affecting

the availability of the organic nitrogen in soil—a preliminary report. Soil Sci. Soc. Am., Proc. **11:** 264–267.
41. BRUCE, A. 1941. Periodicity of nitrification. II. Rubber area. III. Coconut area. Trop. Agr. **96:** 28–81.
42. BUREMA, S. J. and WIERINGA, K. T. 1942. Molybdenum as a growth factor of *Azotobacter chroococcum*. Anatomie van Leeuwenhoek, Jour. Microbiol. & Serol. **8:** 123–133.
43. BURK, D. and LINEWEAVER, H. 1930. The influence of fixed nitrogen on *Azotobacter*. Jour. Bact. **19:** 389–414.
44. BURKHART, L. 1934. Metabolism of etiolated seedlings as affected by ammonium nutrition. Plant Physiol. **9:** 351–358.
45. BURRIS, R. H. 1941. Failure of barley to fix molecular nitrogen (N^{15}). Science **94:** 238–239.
46. ———. 1942. Distribution of isotopic nitrogen in *Azotobacter vinelandii*. Jour. Biol. Chem. **143:** 509–517.
47. ———, EPPLING, F. J., WAHLIN, H. B. and WILSON, P. W. 1943. Studies of biological nitrogen fixation with isotopic nitrogen. Soil Sci. Am., Proc. **7:** 258–262.
48. ——— and WILSON, P. W. 1945. Biological nitrogen fixation. Ann. Rev. Biochem. **14:** 685–708.
49. ——— and ———. 1946. Ammonia as an intermediate in nitrogen fixation by *Azotobacter*. Jour. Bact. **52:** 505–512.
50. CARL, G. C. 1940. Some ecological conditions in a brackish lagoon. Ecology **21:** 65–74.
51. CASAS-CAMPILLO, C. 1947*a*. Bacterias aerobias esporuladas con propiedades antagonistas para *Rhizobium*. Ciencia **8:** 108.
52. ———. 1947*b*. Efecto antibiotico para *Rhizobium* de una fraction organica del suelo. Ciencia **8:** 168–171.
53. ——— and GUERRERO, D. 1948. Inactivacion del bacteriofago de *Rhizobium meliloti* por bacterias aerobias esporuladas. Ciencia **8:** 252–257.
54. CASTELLI, T. 1931. Développement symbiotique d'azoto bactéries et de clostrides azoto fixateurs sur las plaques de terre modelée. Soc. Int. Microbiol. Boll. Sez. Ital. **3:** 359–360.
55. CHAUDHURI, H. 1940. Nitrogen fixation in the rice field soils of Bengal. Nature [London] **145:** 936–937.
56. CHUBAROV, A. 1927. Process of nitrification under conditions of fallow tillage of soil and under natural conditions. Mem. Inst. Agron. Leningrade **4:** 3–20.
57. CLARK, F. E. 1940. Notes on types of bacteria associated with plant roots. Trans. Kansas Acad. Sci. **43:** 75–84.
58. CONN, H. J. 1948. The most abundant groups of bacteria in soil. Bact. Rev. **12:** 257–273.
59. CORBET, A. S. 1935. Recent work on the biological and chemical aspects of nitrification. Ann. Appl. Biol. **22:** 416–419.
60. COX, G. M. and MARTIN, W. P. 1937. Use of a discriminant function for differentiating soils with different *Azotobacter* populations. Iowa State Coll. Jour. Sci. **11:** 323–332.
61. CRAIG, N. and GIRAUD, F. 1926. The reversion of nitrates in the soil under cultural conditions in Mauritius. Mauritius Dept. Agr., Sci. Ser. Bull. 11: 1–19.
62. CULLINAN, F. P. and BATJER, L. P. 1943. Nitrogen, phosphorus and potassium interrelationships in young peach and apple trees. Soil Sci. **55:** 49–60.
63. CULTERA, R. 1946*a*. Photochemical reactions of the oxidation-reduction of NH_4^+ and NO_3^- ions. Gazz. Chim. Ital. **76:** 187–194.
64. ———. 1946*b*. Arable soil in relation to the photochemical oxidation-reduction reactions of the ammonium and nitrate ions. Ann. Chim. Applicata **36:** 245–253.

65. CUTLER, D. W. and BAL, D. V. 1926. Influence of Protozoa on the process of nitrogen fixation by *Azotobacter chroococcum*. Ann. Appl. Biol. **13**: 516–534.
66. ————. 1930. Nitrifying bacteria. Nature [London] **125**: 168.
67. DAVIS, J. F. 1944. Field observations regarding the value of root nodule bacteria. Jour. Am. Soc. Agron. **36**: 869–871.
68. DE, P. K. and SULAIMAN, M. 1950. Fixation of nitrogen in rice soils by algae as influenced by crop, carbon dioxide, and inorganic substances. Soil Sci. **70**: 137–151.
69. DEMOLON, A. and BARBIER, G. 1931. Influence de la constitution physique des sols sur l'allure des phénomènes microbiens dont ils sont le siege. Ann. Agron. [Paris] **1**: 531–535.
70. ———— and DUNEZ, A. 1936. Nouvelles observations sur la bacteriophage et la fatigue des sols cultivés en luzerne. Ann. Agron. [Paris] **6**: 434–454.
71. ———— and ————. 1940. Observations sur la nutrition azotée des Légumineuses. Compt. Rend. Acad. Sci. [Paris] **210**: 676–678.
72. DERX, H. G. 1950. *Beijerinckia*, a new genus of nitrogen-fixing bacteria occurring in tropical soils. Proc. Koninkl. Nederland. Akad. Wet. **53**: 140–147.
73. DESAI, S. V. and FAZAL-UD-DIN. 1936. The nature of nitrification in soil. Indian Jour. Agr. Sci. **6**: 777–783.
74. DHAR, N. R., BHATTACHARYA, A. K. and BISWAS, N. N. 1933. Photonitrification in soil. Soil Sci. **35**: 281–284.
75. ————. 1934. Denitrification in sunlight. Nature [London] **134**: 572–573.
76. ———— and TANDON, S. P. 1936. Influence of temperature on nitrogen fixation by *Azotobacter*. Proc. Nat. Acad. Sci. [India] **6**: 35–39.
77. ———— and SESHACARYULU, E. V. 1936. Nitrogen fixation and *Azotobacter* count on the application of sugars to the soil. 2. Proc. Nat. Acad. Sci. [India] **6**: 244–251.
78. ———— and MUKERJI, S. K. 1936. Nitrogen fixation in soil with cellulosic substances, cow dung and fats. I. Proc. Nat. Acad. Sci. [India] **6**: 289–295.
79. ———— and ————. 1938. New aspects of nitrogen fixation and conservation in the soil. II. Jour. Indian Chem. Soc. **15**: 543–548.
80. ———— and SESHACHARYULU, E. V. 1939. New aspects of nitrogen fixation and conservation in the soil. III. Influence of light on bacterial numbers and nitrogen fixation. Jour. Indian Chem. Soc. **16**: 463–476.
81. D'OLIVEIRA, B. 1939. Can rusts fix nitrogen? Nature [London] **144**: 480.
82. DOROSINSKII, L. M. 1941. The effect of bacteriophage on the development of clover. Mikrobiologiĭa **10**: 208–214.
83. DROBKOV, A. 1945. Effect of radioactive elements upon development of the root-nodule bacteria and upon the assimilation by them of the molecular nitrogen of the atmosphere. Compt. Rend. [Doklady] Acad. Sci. URSS **49**: 224–226.
84. DUFRENOY, J. 1940. The relation of boron to the root-nodules of *Vicia faba*. Growth **4**: 323–326.
85. DYKYJ-SAJFERTOVA, D. and DYKYJ, J. 1941. Influence of nitrogen and potassium on the structure and physiology of sugar beets. Agn. Bot. **23**: 164–177.
86. EFENDIEVA, S. A. 1944. Ustanovlenie sasolennosti pochov pri pomoshchi azotobakternoĭproby. Mikrobiologiĭa **13**: 147–154.

87. Efron, N. A. and Milova, I. E. 1941. The influence of nodule bacteria on sweet clover. Mikrobiologiîa **10:** 456–460.
88. Emerson, F. W. 1935. An ecological reconnaissance in the White Sands, New Mexico. Ecology **16:** 226–233.
89. Fedorov, M. V. 1945. Fixation of atmospheric nitrogen by *Azotobacter* as influenced by the substances reacting with the amino group of the catalyst. Compt. Rend. Acad. Sci. [U.R.S.S.] **49:** 675–678.
90. ————. 1946*a*. Chemistry of fixation of atmospheric nitrogen by *Azotobacter*. The influence of narcotics (ethylurethan and diphenylurea) on the productivity of nitrogen fixation. Mikrobiologiîa **15:** 23–29.
91. ————. 1946*b*. Fixation of atmospheric nitrogen by *Azotobacter* as affected by substances reacting with the carboxyl radical of the catalyst. Compt. Rend. Acad. Sci. [U.R.S.S.] **51:** 63–66.
92. ————. 1946*c*. Chemical mechanism of atmospheric nitrogen fixation by *Azotobacter*. Mikrobiologiîa **15:** 509–518.
93. ————. 1947. Fixation of atmospheric nitrogen by *Azotobacter* as affected by substances entering into reaction with the nitrogen-fixation catalyst as a base. Compt. Rend. Acad. Sci. [U.R.S.S.] **55:** 351–354.
94. ————. 1948*a*. Significance of carbon-linked hydrogen in fixation of molecular nitrogen by *Azotobacter*. Mikrobiologiîa **17:** 208–217.
95. ————. 1948*b*. Fixation of molecular nitrogen by *Azotobacter* in the presence of amides and amino acids. Mikrobiologiîa **17:** 425–434.
96. ————. 1949*a*. Participation of hemin enzyme in fixation of molecular nitrogen by *Azotobacter*. Doklady Akad. Nauk S.S.S.R. **66:** 113–116.
97. ————. 1949*b*. Nitrogen fixation by *Azotobacter* in the presence of surface-active compounds and dehydrating agents. Mikrobiologiîa **18:** 299–309.
98. ————. 1949*c*. The effect of ascorbic acid on atmospheric nitrogen fixation by *Azotobacter*. Doklady Akad. Nauk S.S.S.R. **66:** 945–948.
99. ————. 1949*d*. Two-component structure of the catalyst of nitrogen fixation in *Azotobacter* and the course of the physiological process in fixation of molecular nitrogen. Doklady Akad. Nauk S.S.S.R. **67:** 557–559.
100. Fedorowa-Winogradowa, T. and Gurfein, L. N. 1928. Beiträge zur Frage der Wirkung der Bodenamöben auf das Wachstum und die Entwicklung des *Azotobacter chroococcum* unter Versuchsbedingungen auf sterilem Boden. Centralbl. Bakt. II Abt. **74:** 14–21.
101. Ferguson, C. E. and Albrecht, W. A. 1941. Nitrogen fixation and soil fertility exhaustion by soybeans under different levels of potassium. Mo. Agr. Exp. Sta., Res. Bull. 330: 1–52.
102. Fernandes, F. and Bhat, J. V. 1945. A note on the association of *Chlorococcum humicolum* in roots of *Cycas revoluta*. Current Sci. **14:** 235.
103. Fogg, G. E. 1947. Nitrogen fixation by blue-green algae. Endeavor [London] **6:** 172–175.
104. Fraps, G. S. and Sterges, A. J. 1935. Effect of sunlight on the nitrification of ammonium salts in soils. Soil Sci. **39:** 85–94.
105. Fred, E. B. 1916. Some factors that influence nitrate formation in acid soils. Soil Sci. **1:** 317–338.
106. Frei, H. 1942. Quantitative studies on the assimilation of elementary N from the air by pellicle-forming yeasts. Zentr. Bakt. Parasitenk. II Abt. **104:** 326–365.

107. FULMER, E. I. and CHRISTENSEN, L. M. 1925. The fixation of atmospheric nitrogen by yeast as a function of the hydrogen ion concentration. Jour. Physiol. Chem. **29**: 1415–1418.
108. GAINEY, P. L. and FOWLER, E. 1945. Growth curves of *Azotobacter* at different pH levels. Jour. Agr Res. **70**: 219–236.
109. ————. 1948. The significance of available calcium as a factor limiting growth of *Azotobacter* at pH levels below 6.0. Jour. Agr. Res. **76**: 265–269.
110. ————. 1949. Effect of inoculating a soil with *Azotobacter* upon plant growth and nitrogen balance. Jour. Agr. Res. **78**: 405–411.
111. GEORGI, C. 1935. The influence of the carbohydrate-nitrogen relation on nodule production by red clover. Jour. Agr. Res. **51**: 597–612.
112. GERLACH, M. 1934. Zur Stickstoffsammlung im Ackerboden. Landw. Jahrb. **80**: 73–101.
113. GEST, H. and KAMEN, M. D. 1949. Studies in the metabolism of photosynthetic bacteria. IV. Photochemical production of molecular hydrogen by growing cultures of photosynthetic bacteria. Jour. Bact. **58**: 239–245.
114. GIÖBEL, G. 1926. The relation of the soil nitrogen to nodule development and fixation of nitrogen by certain legumes. N. J. Agr. Exp. Sta., Bull. 436: 3–125.
115. GONICK, W. N. and REUSZER, H. W. 1948. The distribution of *Azotobacter chroococcum* and *Azotobacter vinelandii* in Colorado soils and surface waters. Soil Sci. Soc. Am., Proc. **13**: 251–257.
116. GREAVES, J. E. and CARTER, E. G. 1920. Influence of moisture on bacterial activities of the soil. Soil Sci. **10**: 361–386.
117. ————. 1928. The influence of soluble salts and organic manures on soil nitrogen. Proc. First Int. Cong. Soil Sci. **3**: 213–221.
118. ————, JONES, L. and ANDERSON, A. 1940. The influence of amino acids and proteins on nitrogen fixation by *Azotobacter chroococcum*. Soil Sci. **49**: 9–19.
119. ———— and JONES, L. W. 1944. The influence of temperature on the microflora of the soil. Soil Sci. **58**: 377–387.
120. ———— and BRACKEN, A. F. 1946. Effect of cropping on the nitrogen, phosphorus, and organic carbon content of a dry-farm soil and on the yield of wheat. Soil Sci. **62**: 355–364.
121. GREENE, R. A. 1932. The effect of temperature upon nitrogen fixation by *Azotobacter*. Soil Sci. **33**: 153–161.
122. GRIFFITH, G. and MANNING, H. L. 1950. Nitrate accumulation in Uganda soils. Nature [London] **165**: 571.
123. GROVINEAU, G., GOUNY, P. and LEFEVRE, G. 1948. Nitrification in calcareous soils. Compt. Rend. Acad. Sci. [Paris] **226**: 957–958.
124. HAAS, A. R. C. 1937. Nitrogen in relation to the growth of citrus cuttings in solution cultures. Plant Physiol. **12**: 163–172.
125. HAHN, B. E., OLSON, F. R. and ROBERTS, J. L. 1942. Influence of potassium chloride on nitrification in Bedford silt loam. Soil Sci. **54**: 113–121.
126. HAMPTON, H. E. and ALBRECHT, W. A. 1944. Nitrogen fixation, composition, and growth of soybeans in relation to variable amounts of potassium and calcium. Mo. Agr. Exp. Sta., Res. Bull. 381: 1–36.
127. HARSTON, C. B. and ALBRECHT, W. A. 1943. Soil acidity for improved nutrient delivery and nitrogen fixation. Soil Sci. Soc. Am., Proc. **7**: 247–257.
128. HERISSET, A. 1946. Fixation de l'azote par le *Nostoc commune* Vaucher. Compt. Rend. Acad. Sci. [Paris] **222**: 1127–1129.
129. HERVEY, R. J. and GREAVES, J. E. 1941. Nitrogen fixation by *Azotobacter chroococcum* in the presence of soil Protozoa. Soil Sci. **51**: 85–100.

130. HIRKO, P. 1930. Influence of moisture on nitrification and the mobility and immobility of P_2O_5 and Ca in the soil. Proc. Int. Soc. Soil Sci. **5:** 69.
131. HIRST, C. T. and GREAVES, J. E. 1944. The nitrogen and mineral contents of sugar beet sections. Soil Sci. **58:** 25–34.
132. HOBBS, C. H. 1944. Studies on mineral deficiency in pine. Plant Physiol. **19:** 590–602.
133. HOLLEY, K. T., DUBLIN, T. G. and PICKETT, T. A. 1932. A study of ammonia and nitrate nitrogen for cotton. Ga. Agr. Exp. Sta., Bull. 273.
134. HORNER, C. K. and BURK, D. 1934. Magnesium, calcium and iron requirements for growth of *Azotobacter* in free and fixed nitrogen. Jour. Agr. Res. **48:** 981–995.
135. ———, ———, ALLISON, F. E. and SHERMAN, M. S. 1942. Nitrogen fixation by *Azotobacter* as influenced by molybdenum and vanadium. Jour. Agr. Res. **65:** 173–193.
136. ——— and ALLISON, F. E. 1944. Utilization of fixed nitrogen by *Azotobacter* and influence on nitrogen fixation. Jour. Bact. **47:** 1–14.
137. ———. 1923. Protein synthesis by *Azotobacter*. Jour. Agr. Res. **24:** 263–274.
138. ILVESSALO, Y. 1923. Ein Beitrag zur Frage der Korrelation zwischen den Eigenschaften des Bodens und dem Zuwachs des Waldbestandes. Acta Forestalia Fennica **25.**
139. INGHAM, G. 1938. Nitrogen transformations in the soil. Jour. So. Afr. Chem. Inst. **21:** 59–63.
140. ———. 1940. Nitrogen fixation in South African soils; is it biological? Jour. So. Afr. Chem. Inst. **34:** 11–15.
141. IWASAKI, K. 1930. Weitere Untersuchungen zur Fixation des Luftstickstoffs durch Azotobakter. Biochem. Zeit. **226:** 32–46.
142. JANKE, A., SEKERA, F. and SZILVINYI, A. 1934. Mikrobiologische Bodenuntersuchungen im Lunzer Bebiet. I. Allgemeiner Teil: Zeil und Methodik der Untersuchungen. Standortsfaktoren und Keimge halt. Archiv. Mikrobiol. **5:** 223–245.
143. JENSEN, H. L. 1929. The influence of the carbon: nitrogen ratios of organic material on the mineralization of nitrogen. Jour. Agr. Sci. **19:** 71–82.
144. ———. 1939. The nitrogen economy of wheat soils. With special reference to nonsymbiotic nitrogen fixation. Jour. Austral. Inst. Agr. Sci. **5:** 154–159.
145. ———. 1940. Nitrogen fixation and cellulose decomposition by soil microorganisms. I. Aerobic cellulose-decomposers in association with *Azotobacter*. Proc. Linn. Soc. New So. Wales **65:** 543–556.
146. ———. 1942. Nitrogen fixation in leguminous plants. II. Is symbiotic nitrogen fixation influenced by *Azotobacter*? Proc. Linn. Soc. New So. Wales **67:** 205–212.
147. ———. 1946. The nitrogen-fixing activity of legume root nodules. Austral. Jour. Sci. **9:** 118.
148. ——— and SPENCER, D. 1947. The influence of molybdenum and vanadium on nitrogen fixation by *Cl. butyricum* and related organisms. Proc. Linn. Soc. New So. Wales **72:** 73–86.
149. JONES, W. N. and SMITH, M. L. 1928. The fixation of atmospheric nitrogen by *Phoma radicis callunae*, including a new method for investigating nitrogen fixing in microorganisms. Brit. Jour. Exp. Biol. **6:** 167–189.
150. JORDAN, J. V. and ANDERSON, G. R. 1950. Effect of boron on nitrogen fixation by *Azotobacter*. Soil Sci. **69:** 311–319.

151. JOSHI, N. V. and BISWAS, S. C. 1935. Does photonitrification occur in soils? Trans. Third Int. Congr. Soil Sci. Vol. 3: 104.
152. ———— and ————. 1948. Does photonitrification occur in the soil? Indian Jour. Agr. Sci. **18:** 115–129.
153. KALANTARIAN, P. and PANOSSIAN, A. 1930. *Azotobacter.* Bull. Univ. etat R.S.S.—Armenie No. 5: 221–224.
154. KALINENKO, V. O. 1948. Heterotrophic bacteria as nitrifiers. Pochvovedenie **1948:** 357–363.
155. KATZNELSON, H. and WILSON, J. K. 1941. Occurrence of *Rhizobium meliloti* bacteriophage in soils. Soil Sci. **51:** 59–63.
156. KEILIN, D. and WANG, Y. L. 1945. Haemoglobin in the root nodules of leguminous plants. Nature [London] **155:** 227–229.
157. ———— and SMITH, J. D. 1947. Hemoglobin and nitrogen fixation in root nodules of leguminous plants. Nature [London] **159:** 692–694.
158. KHALIL, F. 1929. The effect of drying on microbiological processes in soils. Zentr. Bakt. Parasitenk. **79:** 93–107.
159. KHAN, D. 1940. The effect of reaction of the medium on the decomposition of the organic matter in soils with various relative contents of carbon and nitrogen. Trans. Dokuchaev Soil Inst. [U.S.S.R.] **23:** 139–145.
160. KORNEEVA, N. P. 1940. Influence of the physico-chemical properties of the soil on bacteriophage. Mikrobiol. Zhurnal (Kiev) **7:** 105–125.
161. KORSAKOVA, M. P. 1928*a*. Chemistry of the reduction of nitrates. Jour. All-Russ. Congr. Bot., Leningrad **1928:** 205–206.
162. ————. 1928*b*. The chemistry of denitrification. II. Compt. Rend. Acad. Sci. U.R.S.S., Leningrad, Ser. A. **1928:** 341–346.
163. KOSTYCHEV, S. P. 1930. Issledovaniia po biocinamike pochv. Trudy Pochvennogo Instituta Imeni V. V. Dokuchaeva. 149–160.
164. KRASIL'NIKOV, N. A., KRISS, A. E. and LITVINOV, M. A. 1936. Mikrobiologischeskaîa kharakteristika rizosfery kul'turnykh rastenii. Microbiologiîa **5:** 87–98.
165. ———— and KORENYAKO, A. I. 1946. Influence of non-nodule bacteria on growth and nitrogen fixation in legumes. Mikrobiologiîa **15:** 417–421.
166. KRISHNA, P. G. 1928. Nitrogen fixation by soil microorganisms. Jour. Agr. Sci. **18:** 432–438.
167. LAMBIN, A. Z. and LAMBINA, T. F. 1940. Acidification and liming of soils as factors affecting the yields of plants. Trudy Omskogo Sel'skokhoz Inst. 4/17: 34–55.
168. LEE, S. B., WILSON, J. B. and WILSON, P. W. 1942. Mechanism of biological nitrogen fixation. X. Hydrogenase in cell-free extracts and intact cells of *Azotobacter.* Jour. Biol. Chem. **144:** 273–281.
169. ———— and WILSON, P. W. 1943. Hydrogenase and N fixation by *Azotobacter.* Jour. Biol. Chem. **151:** 377–385.
170. LEES, H. and QUASTEL, J. H. 1946. Biochemistry of nitrification in soil. 2. The site of soil nitrification. Biochem. Jour. **40:** 815–823.
171. ————. 1948*a*. Effects of various organic materials on soil nitrification. Biochem. Jour. **42:** 528–531.
172. ————. 1948*b*. Immobilization of mineral nitrogen in soils by different organic materials. Biochem. Jour. **42:** 531–534.
173. ————. 1948*c*. Effects of zinc and copper on soil nitrification. Biochem. Jour. **42:** 534–538.
174. LEONARD, O. A., ANDERSON, W. S. and GIEGER, M. 1948. Effect of nutrient level on the growth and chemical composition of sweet potatoes in sand cultures. Plant Physiol. **23:** 223–237.
175. LEROUX, D. 1940. Influence of some trace elements on the combustion

of organic matter and on nitrification in the soil. Compt. Rend. Acad. Sci. [Paris] **210:** 770–772.

176. LIND, C. J. and WILSON, P. W. 1942. Nitrogen fixation by *Azotobacter* in association with other bacteria. Soil Sci. **54:** 105–111.
177. LINDSTROM, E. S., BURRIS, R. H. and WILSON, P. W. 1949. Nitrogen fixation by photosynthetic bacteria. Jour. Bact. **58:** 313–316.
178. LIPMAN, C. B. and TAYLOR, J. K. 1922. Proof of the power of the wheat plant to fix atmospheric nitrogen. Science **56:** 605–606.
179. LIPMAN, J. G. and CONYBEARE, A. B. 1936. Preliminary note on the inventory and balance sheet of plant nutrients in the United States. N. J. Agr. Exp. Sta., Bull. 607: 1–23.
180. LITTLE, H. N. and BURRIS, R. H. 1947. Activity of the red pigment from leguminous root nodules. Jour. Am. Chem. Soc. **69:** 838–841.
181. LOEHWING, W. F. 1937. Root interactions of plants. Bot. Rev. **3:** 195–239.
182. LOITSJANSKAJA, M. S. 1941. On the development of nodule bacteria in roots of alkaloid-containing and alkaloid-free lupine. Mikrobiologiiâ **10:** 15–32.
183. LOO, T. L. 1931. Studies on the absorption of ammonia and nitrate by the roots of *Zea mais* seedlings in relation to the concentration and the actual acidity of the culture solution. Jour. Faculty Agr., Hokkaido Imp. Univ. **30:** 1–118.
184. LUCHETTI, G. 1932. The influence of selenites and tellurites on microorganisms. Boll. ist. Super. agrar. Pisa **8:** 473–490.
185. LYON, T. L. 1918. Influence of higher plants on bacterial activities in soils. Jour. Am. Soc. Agron. **10:** 313–322.
186. MCCALLA, T. M. 1937. Behavior of legume bacteria (*Rhizobium*) in relation to exchangeable calcium and hydrogen ion concentration of the colloidal fraction of the soil. Mo. Agr. Exp. Sta., Res. Bull. 256: 1–44.
187. ———. 1942. Why does H become toxic to soil bacteria? Soil Sci. Soc. Am., Proc. **6:** 165–167.
188. MADHOK, M. R. 1940. Association of legumes and non-legumes. Soil Sci. **49:** 419–429.
189. MAGROU, J. 1944. Role of endotrophic mycorrhizae. Compt. Rend. Acad. Sci. [Paris] **219:** 519–521.
190. MAKRINOW, I. W. 1934. Die biologische Bearbeitung von Pflanzenresten. Zentralbl. Bakt. II Abt. **90:** 154–157.
191. MAMELI DE CALVINO, E. and POLLACCI, G. 1923. The direct assimilation of free nitrogen by plants. A review of recent work on the subject. Torreya **23:** 99–104.
192. MARTIN, W. P. 1940. Distribution and activity of *Azotobacter* in the range and cultivated soils of Arizona. Univ. Ariz. Agr. Exp. Sta., Tech. Bull. 83: 333–369.
193. ———, BUEHRER, T. F. and CASTER, A. B. 1942. Threshold pH value for the nitrification of ammonia in desert soils. Soil Sci. Soc. Am., Proc. **7:** 223–228.
194. MATHESON, D. H. 1947. Cleaning rapid sand filters with chlorine at Hamilton plant. Eng. Contract Rec. **60:** 98–100.
195. MATYASHVILI, S. I. 1947. Influence of boron and molybdenum on morphological and physiological properties of *Azotobacter chroococcum*. Mikrobiologiiâ **16:** 19–31.
196. MENCHIKOVSKY, F. 1933. Notes on the fixation of N in local sandy soil by symbiosis between *Azotobacter*, *Oscillaria* and *Gloeocapsa*. Hadar **6:** 238.
197. MEVIUS, W. and ENGLE, H. 1929. Die Wirkung der Ammoniumsalze in ihrer Abhängigkeit von der Wasserstoffionenkonzentration. Planta **9:** 1–83.

198. MIRCHANDANI, T. J. 1937. Nitrogen status of Indian soils. Proc. Nat. Inst. Sci. [India] **3:** 185–189.
199. MISHUSTIN, E. N. and PROKOSHEV, V. N. 1949. Changes in soil microflora resulting from prolonged use of fertilizers. Mikrobiologiiâ **18:** 30–41.
200. MOORE, B., WHITLEY, E. and WEBSTER, T. A. 1921. Studies of photosynthesis in marine algae. I. Fixation of carbon and nitrogen from inorganic sources in sea water. II. Proc. Royal Soc., B. **92:** 51–60.
201. MOWRY, H. 1933. Symbiotic nitrogen fixation in the genus *Casuarina*. Soil Sci. **36:** 409–422.
202. MUSIL, F. 1946. Carodějné kruhy. Lesnická Práce **25:** 341–355.
203. NATH, B. V. 1940. Reports of the imperial agricultural chemist. Imp. Agr. Res. Inst., New Delhi, Sci. Rep. **1938–1939:** 83–102.
204. NELLER, J. F. 1944. Influence of cropping, rainfall and water table on nitrates in everglades peat. Soil Sci. **57:** 275–280.
205. NEWTON, J. D. 1930. Seasonal fluctuations in numbers of microorganisms and nitrate nitrogen in an Alberta soil. Sci. Agr. **10:** 361–368.
206. NICKELL, L. G. and BURKHOLDER, P. R. 1947. Inhibition of *Azotobacter* by soil actinomycetes. Jour. Am. Soc. Agron. **39:** 771–779.
207. NICOL, H. 1934. The derivation of the nitrogen of crop plants with special reference to associated growth. Biol. Rev. **9:** 383–410.
208. NIGHTINGALE, G. T. 1934. Ammonium and nitrate nutrition of dormant delicious apple trees at 48° F. Bot. Gaz. **95:** 437–452.
209. NILSSON, R. 1942. Äggviteframställning under användande av luftens fria kväve som kvavekälla. K. Landtbruks-Akad. Handl. och Tidskr. [Stockholm] **81:** 326–331.
210. NISS, H. F. and WILSON, P. W. 1947. Hemoprotein from root nodules and nitrogen fixation by *Rhizobium*. Proc. Soc. Exp. Biol. & Med. **66:** 233–235.
211. NORMAN, A. G. 1946*a*. Recent advances in soil microbiology. Soil Sci. Soc. Am., Proc. **1946:** 9–15.
212. ———— and KRAMPITZ, L. O. 1946*b*. The nitrogen nutrition of soybeans. II. Effect of available soil nitrogen on growth and nitrogen fixation. Soil Sci. Soc. Am., Proc. **10:** 191–196.
213. OMELIANSKY, V. 1926. La résistance des cultures d'*Azotobacter chroococcum* à la dessiccation. Compt. Rend. Acad. Sci. [Paris] **183:** 707–708.
214. ORCUTT, R. A. and FRED, E. B. 1935. Light intensity as an inhibiting factor in the fixation of atmospheric nitrogen by Manchu soybeans. Jour. Am. Soc. Agron. **27:** 550–558.
215. PARDO, J. H. 1932. Ammonia vs. nitrate as nitrogen sources for sugar cane. Proc. Fourth Cong. Int. Soc. Sugar Cane Tech., Bull. 13.
216. PARR, C. H. and BOSE, R. D. 1945. Phosphate manuring of legumes. II. Indian Farming **6:** 201–208.
217. PEEVY, W. J. and NORMAN, A. G. 1948. Influence of composition of plant materials on properties of the decomposed residues. Soil Sci. **65:** 209–226.
218. PEKLO, J. and SATAVA, J. 1949. Fixation of free nitrogen by bark beetles. Nature [London] **163:** 336–337.
219. ————. 1949. Symbiosis of *Azotobacter* with insects. Rep. Proc. Fourth Int. Cong. Microbiol. 1947: 477–478.
220. PETHICA, B. A., ROBERTS, E. R. and WINTER, E. R. S. 1949. Role of hydroxylamine in biological fixation of nitrogen. Nature [London] **163:** 408.
221. PHELPS, A. S. and WILSON, P. W. 1941. Occurrence of hydro-

genase in nitrogen-fixing organisms. Proc. Soc. Exp. Biol. & Med. **47:** 473–476.

222. PHILLIS, E. and MASON, T. G. 1943. Memoirs, Cotton Res. Sta., Trinidad, B, **15:** 469. [Not seen; from Bonner]
223. PILLAI, S. C., WADHWANI, T. K., GURBAXANI, M. I. and SUBRAHMANYAN, V. 1948. Observations on nitrite-producing bacteria from different sources and the role of Protozoa in nitrification. Current Sci. **17:** 122–123.
224. PINCK, L. A., ALLISON, F. E. and GADDY, V. L. 1946. The effect of straw and nitrogen on the yield and quantity of nitrogen fixed by soybeans. Jour. Am. Soc. Agron. **38:** 421–431.
225. ————, ———— and ————. 1948. Utilization of nitrogen in cropping systems with and without green manure in the greenhouse. Soil Sci. **66:** 39–52.
226. PLOTHO, O. 1941. Die Synthese der Knollchen an den Wurzeln der Erle. Arch. Mikrobiol. **12:** 1–18.
227. POCHON, J. and LAJUDIE, J. 1948. Action de certains antiseptiques sur la microflore normale du sol. Compt. Rend. Acad. Sci. [Paris] **226:** 2091–2092.
228. POSCHENRIEDER, H., SAMMET, K. and FISCHER, R. 1940. Untersuchungen ueber den Einfluss verschiedener Ernährung mit Kali und Phosphorsäure auf die Ausbildung der Wurzelknollchen und die Tätigkeit der Knöllchenbakterien bei der Sojabohne. Zentralbl. Bakt. II Abt. **102:** 388–395.
229. PRIANISCHNIKOV, D. N. 1923. Sur l'assimilation de l'ammoniaque par les plantes superieures. Comp. Rend. Acad. Sci. [Paris] **177:** 603–606.
230. PURI, A. N., RAI, B. and KAPUR, R. K. 1946. Oxidation of nitrites and oxalates in soils. Soil Sci. **62:** 121–136.
231. PYHOB, E. B. 1926. Possibility of NO_3 formation from N-containing organic materials and from ammonia, without intervention of *Nitrosomonas*. Ber. Bact. Agron. Sta. Moskau **1926:** 189–199.
232. QUISPEL, A. 1947. The influence of the oxidation-reduction potential of the medium upon the growth of *Azotobacter chroococcum*. Anatomie van Leeuwenhoek, Jour. Microbiol. & Serol. **13:** 33–43.
233. RAO, G. G. 1934. Newer aspects of nitrification: I. Soil Sci. **38:** 143–159.
234. RAO, K. A. 1923. A preliminary account of symbiotic N fixation in non-leguminous plants with special reference to *Chomelia asiatica*. Agr. Jour. India **18:** 132–143.
235. REMY, T. 1926. Die Einwirkung zunehmenden Kalgehaltes auf die Lebensäusserungen der bodenbewohnenden Kleinlebewelt. Deut. Landw. Presse **53:** 514.
236. ROBERTS, J. L. and OLSON, F. R. 1942. The influence of fertilizers and season on nonsymbiotic nitrogen fixation in Brookston and Bedford silt loans. Jour. Am. Soc. Agron. **34:** 624–627.
237. ———— and ————. 1944. Influence of phosphorus and potassium on symbiotic nitrogen fixation. Jour. Am. Soc. Agron. **36:** 637–645.
238. ROMMEL, L. G. and HEIBERG, S. O. 1931. Types of humus layer in the forests of northeastern United States. Ecology **12:** 567–608.
239. ————. 1939. The ecological problem of mycotrophy. Ecology **20:** 163–167.
240. ROSENBLUM, E. D. and WILSON, P. W. 1950. Molecular hydrogen and nitrogen fixation by *Clostridium*. Jour. Bact. **59:** 83–91.
241. ROSSI, G. DE. 1933. La nitrification dans le terrain par simple action physico-chemique. Soc. Int. Microbiol. Boll. Sez. Ital. **5:** 132–136.
242. RUSSELL, E. J. and RICHARDS, E. H. 1919. The amount and composition of rain falling at Rothamsted. Jour. Agr. Sci. **9:** 309–337.

243. SCHANDERL, H. 1940. Beweise für die Fähigkeit zur Assimilation des molekularen Stickstoffs durch die Bakterien-symbionten einiger Nichtleguminosen. Gartenbauswiss. **15**: 1–27.
244. ————. 1942*a*. Vergleichende Untersuchungen über den Stickstoffhaushalt von Leguminosen und Nichtleguminosen. Ber. Deut. Bot. Ges. **60**: 86–93.
245. ————. 1942*b*. Assimilation of elemental nitrogen of the air by the yeast symbionts of *Rhagium inquisitor*. Zeit. Morphol. Okol. Tiere **38**: 526–533.
246. ————. 1943. The N content of leguminous and non-leguminous plants. Planta **33**: 424–457.
247. SCHEFFER, F. and KARAPURKAR, Y. M. 1934. Dependence of nitrification on the nature and rate of decomposition of organic materials. Kuhn-Arch. **37**: 143–172.
248. SCHMIDT, O. C. 1948*a*. Zur Frage der Impfung mit *Azotobacter*. II. Zeits. Pflanzenernähr., Düng. u Bodenk. **42**: 148–159.
249. ————. 1948*b*. Über die Wirkung verschiedener Impfpräparate fur Leguminosen. Zeits. Pflanzenernahr., Düng. u. Bodenk. **42**: 268–271.
250. SEN, J. 1929. Is bacterial association a factor in nitrogen assimilation by rice plants? Agr. Jour. India **24**: 229–231.
251. SHIELDS, L. M. 1951. Leaf xeromorphy in dicotyledon species from a gypsum sand deposit. Am. Jour. Bot. **38**: 175–190.
252. ————. 1953. Nitrogen sources and nitrogen content of plants growing in gypsum sand. [In prep.]
253. SHULOV, I. 1912. Sterile cultures of higher plants. Assimilation of nitrogen as ammonia and nitrates. Jour. Exp. Landw. **13**: 200–206.
254. SHUMAKOV, V. S. 1948. The causes that hinder nitrification in forest soils. Pochvovedenie (Pedology) **1948**: 227–236.
255. SIDERIS, C. P., KRAUSS, B. H. and YOUNG, H. Y. 1937. Assimilation of ammonium and nitrate nitrogen from solution cultures by roots of *Pandanus veitchii* hort. and distribution of the various nitrogen fractions and sugars in the stele and cortex. Plant Physiol. **12**: 899–928.
256. SINGH, B. N. and NAIR, K. M. 1939. Is sunlight a factor in nitrogen transformation in soil? Soil Sci. **47**: 285–291.
257. SKINNER, C. E. 1928. Fixation of nitrogen by *Bacterium aerogenes* and related species. Soil Sci. **25**: 195–205.
258. ————. 1930. An explanation of the action of the so-called accessory substance in the association of *Azotobacter* and cellulose decomposing organisms. Jour. Bact. **19**: 149–159.
259. SMITH, N. R., DAWSON, V. T. and WENZEL, M. E. 1946. The effect of certain herbicides on soil microorganisms. Soil Sci. Soc. Am., Proc. **10**: 197–201.
260. SMITH, J. D. 1948. Symbiotic microorganisms of aphids and fixation of atmospheric nitrogen. Nature [London] **162**: 930–931.
261. SNOW, L. M. 1935. A comparative study of the bacterial flora of wind-blown soil: VI. Death Valley, California with summary of six soil studies. Soil Sci. **40**: 181–190.
262. SNYDER, R. M. 1925. Nitrogen fixation by non-leguminous plants. Mich Agr. Exp. Sta., Quart. Bull. 8(1) : 34–36.
263. STAPP, C. 1940. *Azotomonas insolita*, a new aerobic nitrogen-fixing organism. Zentr. Bakt., Parasitenk. II Abt. **102**: 1–9.
264. STARC, A. 1943. Zur Frage der Rhizosphäre und Bodenimpfung mit *Azotobacter*. Arch. Mikrobiol. **13**: 164–181.
265. STARKEY, R. L. 1929. Some influences of the development of higher plants upon the microorganisms in the soil. II. Influence of the stage of plant growth upon abundance of organisms. Soil Sci. **27**: 355–378.

266. STEVENS, F. L. and WITHERS, W. A. 1909. Concerning the existence of non-nitrifying soils. Science **29**: 506–508.
267. STOKES, J. L. 1940. The role of algae in the nitrogen cycle of the soil. Soil Sci. **49**: 265–267.
268. ————. 1941. The relation of algae to the nitrogen economy of the soil. Chron. Bot. **6**: 202–203.
269. SÜCHTING, H. 1949. The nitrogen dynamics of forest soils and the nitrogen nutrition of forest stock. Zeits. Pflanzenernähr Düngung u. Bodenk. **48**: 1–37.
270. SULAIMAN, M. 1941. Influence of light on nitrogen fixation in Dacca soil. Jour. Indian Chem. Soc. **18**: 40–42.
271. ————. 1944. Effect of algal growth on the activity of *Azotobacter* in rice fields. Indian Jour. Agr. Sci. **14**: 277–282.
272. TAM, R. K. and CLARK, H. E. 1943. Effect of chloropicrin and other soil disinfectants on the nitrogen nutrition of the pineapple plant. Soil Sci. **56**: 245–261.
273. THORNTON, H. G. 1936. The present state of our ignorance concerning the nodules of leguminous plants. Sci. Prog. **122**: 236–249.
274. TIEDJENS, V. A. and ROBBINS, W. R. 1931. The use of ammonia and nitrate nitrogen by certain crop plants. N. J. Agr. Exp. Sta., Bull. 526.
275. TIMONIN, M. I. 1949. *Azotobacter* preparation (Azotogen) as fertilizer for cultivated plants. Soil Sci. Soc. Am., Proc. **13**: 246–250.
276. TOMPOS, A. 1948. Nitrogényüjtö novenyek, és a talaj nitrogéntartalma. Kisérletügyi Kozlemények **47**: 21–32.
277. TOTH, L. A., WOLSKY, A. and BATORI, M. 1942. Stickstoffbindung aus der Luft bei den Aphiden und bei den Homoptern (Rhynchota insecta). Zeits. Vergleich. Physiol. **30**: 67–73.
278. ————. 1949. The biological fixation of atmospheric nitrogen by means of microorganisms living in symbiosis with insects. Proc. Int. Cong. Exp. Cytol., Stockholm, **1947**: 304–306.
279. TOVE, S. R., NISS, H. F. and WILSON, P. W. 1950. Fixation of nitrogen 15 by excised nodules of leguminous plants. Jour. Biol. Chem. **184**: 77–82.
280. TROUG, E., GOATES, R. J., GERLOFF, G. C. and BERGER, K. C. 1947. Magnesium-phosphorus relations in plant nutrition. Soil Sci. **63**: 19–25.
281. TROUG, E. 1948. Lime in relation to availability of plant nutrients. Soil Sci. **65**: 1–7.
282. TRUFFANT, G. and BESSZONOFF, N. 1926. Sur la prédominance l'activité des fixateurs anaerobias d'azote dans de sol. Compt. Rend. Acad. Sci. [Paris] **181**: 165–167.
283. TUCAY, J. O. 1933. Nitrifying efficiency of soils. Philippine Agr. **21**: 551–559.
284. ULRICH, A. 1950. Nitrogen fertilization of sugar beet in California. II. Effect upon nitrate-nitrogen content of the petioles and sugar production. Proc. Am. Soc. Sugar Beet Technol. **6**: 372–382.
285. UPPAL, B. N. and PATEL, M. K. 1947. Influence of root excretions and germinating seeds on nitrogen fixation by *Azotobacter*. Proc. Indian Acad. Sci. B. **25**: 173–177.
286. VANDECAVEYE, S. C. and KATZNELSON, H. 1936. Bacteriophage as related to the root nodule bacteria of alfalfa. Jour. Bact. **31**: 465–477.
287. ———— and MOODIE, C. D. 1942. Occurrence and activity of *Azotobacter* in semiarid soils in Washington. Soil Sci. Soc. Am., Proc. **7**: 229–236.
288. VAN NIEL, C. B. 1935. A note on the apparent absence of *Azotobacter* in soils. Arch. Mikrobiol. **6**: 215–218.

289. VERONA, O. and PACI, S. 1931. Quelques recherches sur la bacteriologie des terrains de la maremme de Talamone. Soc. Int. Microbiol. Boll. Sez. Ital. **3**: 203–206.
290. VINOGRADOVA, K. G. 1943. Presence of molybdenum in Leguminosae. Doklady Akad. Nauk. S.S.S.R. **40**: 31–34.
291. VIRTANEN, A. I., HAUSEN, S. V. and LAINE, T. 1936. Excretion of nitrogenous compounds from the root nodules of leguminous plants inoculated with different strains of the nodule organism. Suomen Kemistilehti B, IX. **5**: 1.
292. ————. 1939. Mechanism of symbiotic nitrogen fixation by leguminous plants. Trans. Third Comm. Int. Soc. Soil Sci. Vol. A: 4–19.
293. ————. 1945. Symbiotic nitrogen fixation. Nature [London] **155**: 747–748.
294. ———— and LAINE, T. 1946. Red, brown and green pigments in leguminous root nodules. Nature [London] **157**: 25–26.
295. ————, LINKOLA, M. H. and RAUTANEN, N. 1946. Glutamic acid among the excretion products of legume nodules. Suomen Kemistilehti **19** B: 83–84.
296. ————, JORMA, J., LINKOLA, H. and LINNASALMI, A. 1947*a*. On the relation between nitrogen fixation and leghaemoglobin content of leguminous root nodules. Acta Chem. Scand. **1**: 50–111.
297. ————, ERKAMA, J. and LINKOLA, H. 1947*b*. The relation between nitrogen fixation and leghemoglobin content of leguminous root nodules. Acta Chem. Scand. **1**: 861–870.
298. ———— and LINKOLA, H. 1948. On the antibacterial effect of spore-forming bacteria on the legume bacteria. Suomon Kemistilehti **21** B: 12–13.
299. VOLZ, E. 1941. Nachprüfung der Möglichkeit von nichtbakterieller Stickstoffbindung aus Luft Stickstoff durch Kopplung energieliefernder Reaktionen. Bodenk. u. Pflanzenernahr. **23**: 260–264.
300. WAKSMAN, S. A., HOTCHKISS, M. and CAREY, C. L. 1933. Marine bacteria and their role in the cycle of life in the sea. II. Bacteria concerned in the cycle of nitrogen in the sea. Biol. Bull. **65**: 137–167.
301. ———— and HUTCHINGS, I. J. 1935. The function of cellulose and lignin in the preservation of nitrogen in soils and in composts. Trans. Third Int. Congr. Soil Sci. Vol. 1: 163–167.
302. ————, MADHOK, M. R. and HOLLAENDER, A. 1937. Influence or artificial irradiation upon the oxidation of ammonia and formation of nitrate in soil. Soil Sci. **44**: 441–446.
303. WALKER, R. H., SULLIVAN, J. L. and POHLMAN, G. G. 1930. The spontaneous culture method for studying the non-symbiotic nitrogen-fixing bacteria of soils. Jour. Am. Soc. Agron. **22**: 642–648.
304. ————. 1931. Studies on nitrogen fixation in some Iowa soils. Proc. Iowa Acad. Sci. **37**: 75.
305. WALKLEY, J. 1940. Protein synthesis in mature and senescent leaves of barley. New Phytol. **39**: 362–369.
306. WARING, E. J. 1950. Sawdust as a soil improver causes nitrogen deficiency in vegetable crops. Agr. Gaz. New So. Wales **61**: 73–76.
307. WAYNICK, D. D. and WOODHOUSE, ——. 1919. By what steps does *Azotobacter* fix nitrogen? Cal. Agr. Exp. Sta., Ann. Rpt. **1918–1919**: 62–63.
308. WERNER, A. R. 1935. The biological activators of *Azotobacter*. Compt. Rend. Acad. Sci. [U.R.S.S.] **4**: 57–60.
309. ————. 1945. On salt resistance of *Azotobacter*. Compt. Rend. Acad. Sci. [U.R.S.S.] **47**: 301–303.
310. WHITE, J. W. 1940. Nitrogen-fixation microorganisms. Penna. Agr. Exp. Sta., Bull. 399: 19–20.

311. WILLIS, W. H. and WALKER, R. H. 1931. Anaerobic nitrogen fixation in some Iowa soils. Proc. Iowa Acad. Sci. **38:** 293–298.
312. ————. 1934. Metabolism of some nitrogen-fixing *Clostridia*. Iowa Agr. Exp. Sta., Res. Bull. **173:** 255–284.
313. WILSON, B D. 1921. Nitrogen in the rainwater at Ithaca, N. Y. Soil Sci. **11:** 101–110.
314. WILSON, J. B. and WILSON, P. W. 1942. Hydrogen in the metabolism of *Azotobacter*. Jour. Bact. **44:** 250–251.
315. ———— and ————. 1943. Action of inhibitors on hydrogenase in *Azotobacter*. Gen. Physiol. **26:** 277–286.
316. WILSON, J. K. 1934. Longevity of *Rhizobium japonicum* in relation to its symbiont on the soil. New York (Cornell) Agr. Exp. Sta., Mem. **162:** 1–11.
317. ———— and NAIR, K. M. 1948. The latitude between the pH values of nodules and the tissues of leguminous plants. Soil Sci. Soc. Am., Proc. **12:** 243–245.
318. WILSON, P. W. 1935. The carbohydrate-nitrogen relation in symbiotic nitrogen fixation. Wisc. Agr. Exp. Sta., Res. Bull. 129: 1–40.
319. ————. 1937. Symbiotic nitrogen-fixation by the Leguminosae. Bot. Rev. **3:** 365–399.
320. ————, LEE, S. B. and WYSS, O. 1941. Mechanism of symbiotic nitrogen fixation. V. Nature of inhibition by hydrogen. Jour. Biol. Chem. **139:** 91–101.
321. ————, BURRIS, R. H. and COFFEE, W. B. 1943. Hydrogenase and symbiotic nitrogen fixation. Jour. Biol. Chem. **147:** 475–481.
322. ————, HULL, J. F. and BURRIS, R. H. 1943. Competition between free and combined nitrogen in nutrition of *Azotobacter*. Proc. Nat. Acad. Sci. **29:** 289–294.
323. ———— and BURRIS, R. H. 1944. Carbon monoxide as an inhibitor of nitrogen fixation by the alga *Nostoc muscorum*. Jour. Bact. **47:** 410–411.
324. ———— and ————. 1947. The mechanism of biological nitrogen fixation. Bact. Rev. **11:** 41–73.
325. WINOGRADSKY, S. and WINOGRADSKY, H. 1933. Études sur la microbiologie du sol. VII. Nouvelles recherches sur les organisms de la nitrification Ann. Inst. Pasteur **50:** 350–432.
326. WITHERS, W. A. and FRAPS, C. S. 1902. Nitrification in different soils. Agr. Exp. Sta., 25th Ann. Rep. **1902:** 31–41.
327. WOOD, J G. 1945. Nitrogenous constituents of plants. Ann. Rev. Biochem. **14:** 665–684.
328. WYSS, O. and WILSON, P. W. 1941. Mechanism of biological nitrogen fixation. VI. Inhibition of *Azotobacter* by hydrogen. Proc. Nat. Acad. Sci. **27:** 162–168.
329. ————, LIND, C. J., WILSON, J. B. and WILSON, P. W. 1941. Mechanism of biological nitrogen fixation. VII. Molecular hydrogen and the pN_2 function of *Azotobacter*. Biochem. Jour. **35:** 845–854.
330. ———— and WYSS, M. B. 1950. Mutants of *Azotobacter* which do not fix nitrogen. Jour. Bact. **59:** 287–291.
331. YEGIAN, H. M. and EISENMENGER, W. S. 1940. Effect of arsenious oxide, arsenic oxide and antimony oxide on soil and plant growth. Mass. Agr. Exp. Sta., Ann. Rep. **1939:** 11.
332. YOSHIMURA, K. 1922. Nitrification in *Cycas revoluta*. Wiss. Mitt. Land- u. Forstw. Hochschule Kagoshima **5:** 35–39.
333. ZOBELL, C. E. 1946. Marine microbiology. 208 pp.
334. ZONN, S. V. 1940. Dynamics of nitrogen compounds in cultivated soils of sand deserts. Pedology [U.S.S.R.] **1940:** 68–80.
335. ZOOND, A. 1926. The relation of combined nitrogen to the physiological activity of *Azotobacter*. Brit. Jour. Exp. Biol. **4:** 105–113.

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